Chapter 8

EVALUATION OF THE THERMAL ENVIRONMENT

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INTRODUCTION

From General George Washington's successful winter attack in Trenton, New Jersey, on December 26, 1776 to present operations in the heat of Iraq and the cold and altitude of the Afghanistan mountains, the environment—as represented primarily by meteorological extremes—has played a role in military operations. Although, on occasion, a catastrophic weather event or a major storm can impact a military operation directly, the majority of medical problems related to the thermal state of soldiers result from their exposure to multiple physical and environmental stress factors that, in combination, might produce chronic or acute physiological strain.

Perhaps because exposure to the physical environment is a persistent but not dramatic factor relative to other tactical and medical concerns, the prevention of environmental injuries related to the weather is often a secondary concern. The prevention of thermal environmental injuries is often not a command priority until a specific ailment (eg, frostbite, hypothermia, or heatstroke) reaches a level that significantly impacts operations or captures media attention. In addition, knowledge of the basic factors involved in thermal stress, particularly meteorology, is not part of classical medical education.

Within the US military, the weather mission is not always a priority for the Army, because the Air Force is assigned primary responsibility for weather. Thus, one cannot fault the medical staff for not being meteorologists. However, for medical personnel operating in the field, having a basic understanding of how weather impacts soldiers can be critical. The purpose of this chapter is to present the basic information regarding the collection of weather data—relating the data to the actual science of heat exchange—and to review methods that allow the interpretation of weather data into practical applications for the management and prevention of morbidity associated with the thermal elements of the environment.

THE ENVIRONMENT

Definition of Environment

At the most basic level, environment is defined as the surroundings of an object, organism, population, or system. By that definition, the environment can be virtually the universe. A more practical and limited definition is necessary, as any reference to the environment is only meaningful in the context of a specific focus. For military medicine, the obvious focus is military personnel. To further reduce the scope of the environment to manageable levels, the description should be limited to factors that may have a specific effect on the individual or population. Thus, it is meaningful to refer to the social, psychological, or physical environment rather than the totality of the environment.

Definition of Thermal Environment

The primary effect of the environment on military personnel is that of ambient conditions on heat exchange. At a given point in time and space, an individual who occupies that point experiences a specific set of physical conditions. Those conditions that determine the potential for heat exchange between the individual and the surrounding environment define the thermal environment. Thus, the thermal environment is defined as those aspects of the physical surroundings of the individual or population that directly affect the potential for heat exchange between the subject or population and its environment. In terms of environmental stress, the thermal environment represents the primary stress potential of the physical environment. The actual strain experienced is dependent on the thermal environment, certain physical characteristics of the individual (eg, posture, insulation, or clothing), and human physiology (hydration, energy reserves, metabolic rate, and activity level).

Energy Balance Equation

The energy balance for an individual can be written as:

$$(1)\ \dot{M} \pm \dot{E} \pm \dot{R} \pm \dot{C} \pm \dot{K} \pm \dot{W}_k \pm \dot{S} = 0\ [W].$$

The variables are metabolism (M), evaporative heat loss (E), radiative heat exchange (R), convection (C), conductance (K), work (W_k), and storage (S). Significant changes in S, as reflected by changes in body temperature, are indications of thermal strain. E, R, C, and K are the environmental pathways for heat transfer. These pathways are not measured directly, however. Instead, measurements are made of the meteorological parameters that determine the potential for transfer along each pathway.

The whole-body equation is expressed in terms of the rate of change in an energy flux (units in W or $J \bullet s^{-1}$), but almost all heat exchanges occur through the body surface. It is therefore often preferable to express heat exchange parameters in relation to the skin surface area involved in heat exchange as density fluxes (W • m^{-2}). It is also more meaningful to reorder the equation to indicate that the final balance might result in a change in the storage term, S.

(2) $S = M - (\pm W_k) \pm E \pm R \pm C \pm K$ [W • m^{-2}]
(3) $\Delta S = 1{,}000 \bullet c_b \bullet m \bullet \Delta T_b \div (\Delta t \bullet A_D)$ [W • m^{-2}].

The value of expressing the energy balance in terms of S is that any change in storage (ΔS), during time interval Δt, will result in a change in body temperature (ΔT_b). The practical significance is that any change in measurable body temperature indicates a shift in the energy balance of the body. Hence, monitoring body temperature will provide a direct indication of the thermal state of the body. The specific heat of body tissue (c_b) is 3.5 kJ • (kg • K)$^{-1}$.[1] Body mass (m) in kilograms and height (ht) in meters can be used to estimate the Dubois (A_D) body surface area.[2]

(4) $A_D = 0.202\ \mathrm{m}^{0.425}\ \mathrm{ht}^{0.725}$ [m^2].

A_D is used to approximate the body surface area involved in convective, radiative, and evaporative heat exchange, but not conductance.

Biophysical/Environmental Variables

Four general environmental parameters determine the potential for heat exchange between an object and the environment. The first three parameters—(1) temperature, (2) wind speed, and (3) radiation—determine dry or sensible heat exchange potential. The fourth parameter, water vapor pressure (humidity), determines the potential for insensible heat exchange that involves a phase change from liquid to vapor.

Conductance. Conductance is heat exchange between a surface and a solid. It is dependent on the temperature difference (ΔT) between the body surface and the other solid surface, the thermal conductivity of the material (k_c), and the distance (l) through which the heat is conducted.

(5) $K = (k_c / l) \bullet \Delta T$ [W • m^{-2}].

To compute actual heat loss, the area of surface contact (A_c) must also be known. For a standing person, the contact area for conductance is through the soles of the feet or footwear. Unless the surface temperature is unusually high or low and the soles are poorly insulated, conductance is usually negligible. Heat loss from even a very small surface area can be important. For an astronaut handling cold-soaked tools on an extravehicular activity, an individual repairing / refueling a vehicle in extreme cold with inadequate handwear, or an injured soldier or rifleman lying / sleeping on frozen ground, conductance can be a significant concern. A combination of radiant heating and conductance quickly teaches vehicle crewmen to protect themselves from the surface of armored vehicles exposed to direct sunlight in the desert.

Convection. Convection is heat transfer through a fluid medium, normally air or water. A hot blast of air or a cool breeze is a sensory interpretation of convective heat exchange. The general equation for convection is driven by the difference between mean skin or surface temperature ($\overline{T}_s$) and air temperature (T_a).

(6) $C = h_c \bullet (\overline{T}_s - T_a)$ [W • m^{-2}].

The convective heat transfer coefficient h_c is dependent on the density, viscosity, and velocity of the fluid. There are two types of convection: (1) free and (2) forced. Free convection involves still or very low-velocity fluids, whereas forced convection dominates at higher fluid velocities. Free convection would occur if a heated rock were placed in still water. By warming the surrounding water, a pattern of fluid densities and temperatures would form around the rock. If the object had been heated at a constant rate rather than cooled, that pattern would stabilize. Forced convection is equivalent to placing the same rock into a flowing stream. The patterns of temperature and density that form in the stream flow are driven in part by the mechanical interaction of the rock and the flowing water, whereas in still water the primary factor is a small buoyancy flow from warming of the surrounding water.

The practical significance of free versus forced convection is that the convective heat transfer coefficient h_c is calculated with slightly different parameters for each type of convection. Free convection dominates in still fluids, and forced convection dominates above 0.3 m • s^{-1}.[3] In the narrow zone between those two thresholds, both free and forced convection must be considered.[4] When forced convection dominates, h_c for a standing individual is roughly proportional to the square root of the air velocity (u). As a consequence, a velocity change of 0.5 m • s^{-1} has a relatively more significant effect on h_c at low wind speeds (below 2.5 m • s^{-1}) than at higher wind speeds.

To calculate h_c for forced convection in air without the additional effects of the individual parameters of motion or clothing requires a series of calculations[4,5]:

Thermal conductivity of air,

(7) $k_f = 2.41 \bullet 10^{-2} + 7.8 \bullet 10^{-5} \bullet T_a$ [W • m^{-2} • °C^{-1}].

Kinematic viscosity of air,

(8) $\nu = 1.33 \bullet 10^{-5} + 9.0 \bullet 10^{-8} \bullet T_a$ [$m^2 \bullet s^{-1}$].

Reynolds number,

(9) $Re = u \bullet L/\nu$ [N.D.]

and the Nusselt number,

(10) $Nu = c Pr^a Re^b$ [N.D.]
(11) $Nu = c'' Re^b$ [N.D.]
(12) $h_c = Nu \bullet k_f / L$ [$W \bullet m^{-2} \bullet K^{-1}$].

The characteristic dimension (L) for a standing cylinder is the diameter (m), and approximate values for c'' and b are 0.33 and 0.55.[6] The Prandlt number (Pr) is assumed to be a constant (0.72) for air temperatures in the 10° to 50°C range, as is the shape factor (a) for a cylinder.[6] The actual rate of heat transfer is not determined wholly by environmental conditions. The convective heat transfer coefficient (h_c) is also determined, in part, by the shape or posture of the individual, as well as by the velocity and other properties of the fluid. The majority of physiological research assumes a standing or walking subject. The shape factor[4,7] for a patient on a litter on the ground is not the same as it is for a standing person. The shape factor would not only differ with posture, but also there would be a parallel equation for free convection at lower air velocities, and clothing and motion would also alter convective heat transfer.

Because of the greater density of water, the rate of heat loss in water is much higher than it is in air. In water, temperature has an effect that is 77 times greater for a nude person at rest in still water than the same temperature difference in air.[8–10] Both activity and water flow will increase the rate of heat loss. A relatively small difference in the temperature gradient between a body and the surrounding water has a much more significant effect on an individual's thermal balance. The danger of water immersion was reinforced by the deaths of four Ranger students following a stream-crossing exercise at Florida's Eglin Air Force Base. The estimated air and water temperatures were 17° to 18°C and 12° to 15°C, respectively.[11]

It is difficult to separate the environmental potential for convective heat loss from the effects of clothing and activity. In a fluid, a series of layers of homogeneous temperature and velocity form about the body surface; this is collectively referred to as the *boundary layer*. By modifying the rate of heat transfer between the surface and the environment, this layer acts as insulation between the body surface and the environment. The thickness and stability of the boundary layer is dependent on the velocity and turbulence of the fluid. Boundary layers are more stable when the fluid flow is streamlined (laminar) rather than turbulent. Extreme turbulence can disrupt the formation or stability of a boundary layer, increasing heat loss.

Convection is also modified by body motion (the *pendulum effect*), the movement of air within clothing and in and out of clothing through openings (pumping or ventilation), and clothing insulation. Another clothing interaction occurs when wind penetrates clothing, thereby reducing the effective insulation. Such effects fall outside the scope of this chapter, but some understanding of how these dynamic, physical factors affect convective heat exchange is useful.

The pendulum effect[12] results from the motion of extremities. The effect of motion has been studied by mounting naphthalene discs on both human subjects[6] and mannequins that simulate walking motion.[13] Empirical equations for calculating h_C during different activities[14] can be used to compensate for the effect of motion on convection. Another approach is to calculate an effective air velocity (v_e) that assumes that the effect of the observed air velocity is enhanced by body motion and that body motion is proportional to whole-body metabolic rate ($\dot{M}$).[15]

(13) $v_e = v_a + 0.004\ (\dot{M} - 105)$ [$m \bullet s^{-1}$]

Measured air velocity (u or v_a) and effective air velocity (v_e) are measured in meters/second. Corrections for only the pendulum effect are adequate for the nude state. The effect of clothing insulation can be estimated by calculating a thermal efficiency factor (F_{cl}) from the intrinsic insulation of clothing (I_{cl}) and boundary layer (I_a), as proposed by Burton in Gagge and Nishi.[14] The F_{cl} value for a nude individual is 1 and always less than 1 when clothing is worn. Some investigators feel that a *pumping coefficient* that adjusts for the pendulum effects and air exchange from both air movement within the clothing and ventilation should be incorporated into the equations. The combination of clothing and motion has been studied in human subjects[16,17] and walking mannequins.[18,19] Tests were often conducted with variable wind speeds to determine the contribution of wind penetration. There have been several approaches to quantifying this pumping effect. One approach is to treat the effects of motion as a convective effect by increasing the heat transfer convection. The other approach is to express the effect as a reduction in clothing insulation, which is possible because clothing insulation is partially a resistance to convective heat exchange.

Convection is an important heat exchange pathway in the cold. The windchill index[20] predicts cold tolerance and injury on the basis of convection heat loss. In the heat, evaporation is usually more important in maintaining homeostasis, but convection is an important pathway for heat exchange in some circumstances. When air temperature is greater than skin temperature, the normal direction of convective heat exchange is reversed, the body will gain heat from the environment, and a cooling breeze becomes a warming breeze. Another situation is the relative importance of evaporative versus convective cooling. Normally, evaporative heat loss is the most effective means of transferring heat to the environment; but, in conditions of extremely high humidity or when impermeable clothing is worn (eg, the Suit, Contamination Avoidance, Liquid Protective [SCALP] or Toxicological Agent Protective [TAP] chemical ensembles), evaporative transfer is greatly reduced or blocked and the primary source of cooling is convective heat loss.

Radiation. Radiation is often equated with direct sunlight and *solar load*. Radiation from the sun interacts with the atmosphere before reaching the body surface. The total or net radiant term in the energy balance equation is the sum of six different heat transfer components. Five of these components are incoming from environmental sources. Solar load is a combination of three of those components: (1) direct, (2) reflected, and (3) scattered solar radiation. The other three components follow: (4) incoming ground thermal radiation, (5) diffuse or sky thermal radiation, and (6) outgoing thermal radiation emitted from the body surfaces (Exhibit 8-1).

Natural nonionizing radiation from the ultraviolet (UV) to thermal or near infrared (IR) spectrum (200 to $8 \bullet 10^4$ nm) is an important component in determining an individual's thermal balance. The wavelength of nonionizing radiation is dependent on the temperature of the radiating surfaces (Wien's law). The sun—which is a large, extremely high-temperature source (6,000 K)—is the principal source of natural radiation. In an outdoor environment, the ultimate source of most radiation is the sun.

Radiation is normally categorized as short-wave (solar) radiation and long-wave (IR or thermal) radiation. UV radiation in the 200- to 400-nm range is included in the discussion of the short-wave radiation component. Although it is important at the cellular level in terms of cell damage and vitamin D production (see Chapter 9), UV contributes little to the thermal load. Visible light (400–750 nm) is detectable by the human eye; the colors seen are actually the light that is reflected by surfaces. Much of the long-wave radiation is absorbed by water in the atmosphere and reemitted rather than transmitted directly through the atmosphere as direct beam radiation. Radiation—particularly in the visible spectrum (400–750 nm)—that is transmitted from the sun through the Earth's atmosphere to the surface without being absorbed and reemitted is classified as solar radiation. Solar radiation includes some near-IR radiation.

Solar radiation is divided into direct, diffuse, and reflected solar radiation. The amount of direct solar radiation that reaches the body surface (Figure 8-1) is dependent on the intensity of the direct rays and a combination of the body surface area, posture, and position of the body relative to the elevation (solar angle) and direction (azimuth) of the sun.[21,22] Diffuse solar radiation consists of short-wave radiation that is scattered or reflected downward as it passes through the clouds and atmosphere. In contrast to direct solar radiation, diffuse solar radiation is assumed to be an isotropic source, so the intensity of diffuse radiation is more or less equal on all exposed surfaces regardless of the angle of incidence. On overcast days, all radiation from the sky is diffuse.

Reflected solar radiation is solar radiation (direct and diffuse) that is reflected back from the surface. The intensity of the reflected radiation depends on the intensity of the incoming radiation and the reflectivity or albedo of the surface. Ice, snow, smooth rock, and sand have high albedos. Normally, the ground reflects incoming radiation equally in all directions; therefore, like diffuse radiation, reflected radiation is isotropic. Topography can also affect reflection. In alpine areas, the walls of a south-facing cirque can act like a parabolic mirror, capturing and intensifying the incoming solar radiation so that the cirque functions like a low-temperature solar oven[23] (Figure 8-2). At higher elevations, a combination of the thinner atmosphere, the high albedo of smooth rock, ice or snow, and terrain features might significantly increase the total amount of incoming solar radiation (including UV radiation) and, thus in addition to warming, an increased potential for sunburn (Exhibit 8-1).

The remaining radiation components are in the thermal or IR spectral range (800–$808 \bullet 10^4$ nm). According to the Stefan-Boltzmann equation, an object emits long-wave radiation (R_b):

$$(14) \quad R_b = \sigma \bullet T_K^4 \; [\mathrm{W} \bullet \mathrm{m}^{-2}].$$

The Stefan-Boltzmann constant (σ) is $5.67 \bullet 10^{-8}$ $\mathrm{W} \bullet \mathrm{m}^{-2} \bullet \mathrm{K}^{-4}$, and $\underline{T}_K$ is the surface temperature in degrees Kelvin ($\overline{T}_s$ + 273). The atmosphere absorbs some of the radiation that reaches the outer atmosphere. Ozone absorbs UV radiation, and water molecules absorb thermal (IR) energy. Energy that is absorbed into the atmosphere warms the upper atmosphere. Some of this energy can be remitted at a different wavelength, depending

EXHIBIT 8-1

SOLAR LOAD

Importance of Solar Load

The importance of radiation and, more specifically, the solar load ($\dot{Q}_s$) to the overall level of environmental thermal stress is the subject of some debate. The soldier in the field knows that solar radiation is important. Conversely, environmental physiologists have tended to treat $\dot{Q}_s$ as a relatively minor contributor to the overall energy balance of humans. The methods for estimating radiant load are often based on relatively crude instruments, such as black globe thermometers; but, as is often the case, direct measurements of radiation are completely absent. Until recently, popular media weather reports offered the public only generalities regarding solar radiation (eg, sunny, partially cloudy, or overcast). Indices for ultraviolet exposure and the potential hazards of sunburn have appeared in local weather forecasts during the summer months and year-round in the subtropics (see Chapter 9, Exhibit 9-6). Military meteorological databases do not generally record information regarding solar radiation unless black globe temperatures have been incorporated into wet bulb globe temperature values. There is an apparent discrepancy between the perceptions of field soldiers and their scientific support regarding solar radiation.

As Lotens and Pieters[1] have indicated, the real importance of $\dot{Q}_s$ occurs when the overall level of thermal stress is high. A radiant gain of 50 W is relatively small; however, if not counterbalanced by an increase in evaporative or convective heat loss, this small imbalance will represent the continual accumulation or storage of energy within the body tissues and a slow, gradual increase in body temperature. When overall stress levels hover at a critical threshold, a small heat gain can be the factor that upsets the balance.

A simplified calculation for a whole-body heat storage would be:

(1) $\Delta S' = c_p \bullet m \bullet \Delta T_b$ [kJ].

The specific heat of body tissue (c_p) is approximately 3.49 kJ • kg^{-1} • °K^{-1}. We can assume that, at a rectal temperature (T_{re}) of approximately 39.5°C, 50% of a military population would exhibit hyperthermic symptoms. Assuming that a neutral initial T_{re} is 37°C, an increase in T_{re} to 39.5°C approximates an increase in body temperature (ΔT_b) of 2.5°C. For a 70-kg individual, if $\dot{Q}_s = 50$ W, constant exposure to that level of solar load would result in hyperthermia in approximately 4 h.

(2) $\Delta S' = 3.49 \bullet 70 \bullet 2.5$ [kJ]
$= 610$ kJ
$= 610 \bullet 10^3$ J.

(3) $\dot{Q}_s = 50$ [W = J • s^{-1}].

(4) $t = 610 \bullet 10^3 \div 50$ [s]
$= 1.22 \bullet 10^4 \div 3{,}600$ [h]
$= 3.4$ h.

For $\dot{Q}_s = 200$ W, the estimated time to hyperthermia would be one-fourth, or approximately 51 min. In actuality, most people would not "cook-off" in 51 min. Instead, thermoregulatory mechanisms, particularly the sweat mechanism, would be strained to compensate for an additional 200 W.

Breckenridge and Pratt[2] demonstrated how the solar load was offset by an increase in evaporation by using the increase in evaporative loss to estimate difference in solar load on soldiers wearing different colors and shades of uniforms. They estimated the solar load for soldiers in a black uniform to be 169 W (145 kg-cal • h^{-1}) and for soldiers in a white uniform to be 107 W (92 kg-cal • h^{-1})—a difference of 62 W. Estimates for green and khaki uniforms made the following year were 131 W and 107 W, respectively, which is a smaller difference of 24 W.

The question posed by Breckenridge and Pratt[2] and other empirical studies[3,4] that found $\dot{Q}_s$ for clothed mannequins ranging from 11 to 166 W is whether or not the solar contribution to energy balance is significant. The general consensus of environmental physiologists and modelers has been that the importance of $\dot{Q}_s$ relative to other thermoregulatory factors is small and that the additional effort required to obtain a more accurate estimate of $\dot{Q}_s$ is not justified. The corollary to this conclusion is that, if there is only a limited need to quantify $\dot{Q}_s$ accurately, there is less need to be

(**Exhibit 8-1** *continues*)

Exhibit 8-1 *continued*

concerned about any difference in between uniforms. The preceding calculations, which demonstrate the potential impact of even a 50 W $\dot{Q}_s$, suggest that solar radiation can be an important factor in thermal balance, but this does not directly address the issue of whether or not a more accurate estimate of $\dot{Q}_s$ is a priority.

Clothing, Color, and $\dot{Q}_s$

It would seem intuitively obvious to anyone standing in direct sunlight that exposure to solar radiation is a significant factor; yet, when energy balance equations are computed, the relative contribution of radiation to the overall energy balance can seem relatively small. Converting those observations to a complete understanding of the full impact of exposure to radiation under field conditions is difficult. Sunburn is a clear hazard, and the degree or severity of the burn can be directly related to the cumulative exposure to total solar radiation, but is not necessarily a reliable indicator of $\dot{Q}_s$ because sunburn impacts bare skin, whereas $\dot{Q}_s$ can be mitigated by clothing. Conversely, the change attributed to moving from full sunlight to shade is quite real, but some of the effect can be from thermal or long-wave radiation being reemitted by the ground or sun-heated walls.

One source of some confusion regarding solar radiation is an apparent paradox; $\dot{Q}_s$ is smaller for clothed individuals than nude individuals. The intuitive response is that, because clothed individuals are warmer than near-nude individuals in the same environment, $\dot{Q}_s$ should be greater when clothed. When you go to the beach, would you put on clothing to reduce your $\dot{Q}_s$? Actually, the answer is yes. Just as you would wear clothing to reduce your ultraviolet exposure (and sunburn), clothing will reduce the absorption of solar energy in the longer wavelengths. The apparent paradox happens because, whereas clothing reduces solar gain, it also reduces heat loss by convection and evaporation. Because radiation is usually a smaller factor in the overall heat balance, the net result is that the clothed state is warmer than the nude state. But, if you want a greater $\dot{Q}_s$, take off your clothing.

In respect to solar load ($\dot{Q}_s$), the body is essentially a solar collector. The total amount of energy absorbed by the collector is dependent on the intensity of the solar radiation (I), the surface absorptivity (α) and transmission (τ), and the exposed surface area (A). For bare skin, absorptivity (α) varies with the degree of skin pigmentation. The approximate range of α is 0.4 to 0.9, but there is considerable variability between people and source wavelength.[5–8]

Clothing modifies $\dot{Q}_s$ in two ways: (1) it modifies all energy exchange pathways by changing the areas for energy exchange and (2) it modifies the rate of heat transfer. It slightly increases the effective absorption surface area (A_e) and modifies the amount of radiation that is absorbed. Clothing increases the outer surface just as increasing the diameter of any cylinder would increase its surface area. A clothing area factor (f_{cl}) is used to adjust A_e for clothing.

The second factor is clothing insulation. Clothing insulation refers to the resistance of clothing to heat transfer by convection and radiation. In practice, clothing insulation decreases the rate of heat transfer by convection, radiation, and conductance. Radiation that is transmitted directly through clothing mass retains its full wavelength distribution, whereas radiation that is absorbed at the clothing surface can heat the clothing surface or increase the temperature of the clothing layer. Some absorbed radiation can be re-reflected multiple times within the clothing material and eventually reach the body surface without any change in wavelength. This reflected solar component is technically transmitted rather than absorbed. Solar radiation that is absorbed by the clothing can be stored in the clothing layer, thereby raising clothing temperatures, or it can be lost by emission, conductance, or convection to the body or the environment. Breckenridge and Goldman[3,4] used an insulation efficiency factor (U), derived from clothing insulation values, to indicate the portion of absorbed solar radiation that was eventually transferred to the body.

Data sources: (1) Lotens WA, Pieters AMJ. Transfer of radiative heat through clothing ensembles. *Ergonomics*. 1995;38:1132–1155. (2) Breckenridge JR, Pratt RL. *Effects of Clothing Color on Solar Heat Load*. Natick, Mass: Environmental Protection Branch, Quartermaster Research and Engineering Center; 1961. Technical Report EP-155. (3) Breckenridge JR, Goldman RF. Solar heat load in man. *J Appl Physiol*. 1971;31:659–721. (4) Breckenridge JR, Goldman RF. Human solar heat load. *ASHRAE Trans*. 1972;78:110–119. (5) Hardy JD. Physiological effect of high intensity infrared heating. *ASHRAE J*. 1962;4:36–42. (6) Roller WL, Goldman RF. Prediction of solar heat load on man. *J Appl Physiol*. 1968;24:717–721. (7) Fanger PO. *Thermal Comfort*. New York, NY: McGraw-Hill; 1970. (8) McIntyre DA. *Indoor Climate*. Essex, England: Applied Science Publishers Ltd; 1980.

on the temperature of the emitting molecules in accordance with the Stefan-Boltzmann equation. The source of this sky thermal radiation is the atmosphere; thus, it is another diffuse, isotropic source. In a similar manner, a portion of the radiation striking the earth might be absorbed, thereby warming the ground. Ground thermal radiation can be calculated in the same manner as a function of surface temperature. Incoming thermal radiation is isotropic and absorbed over the same surface as diffuse and reflected solar radiation.

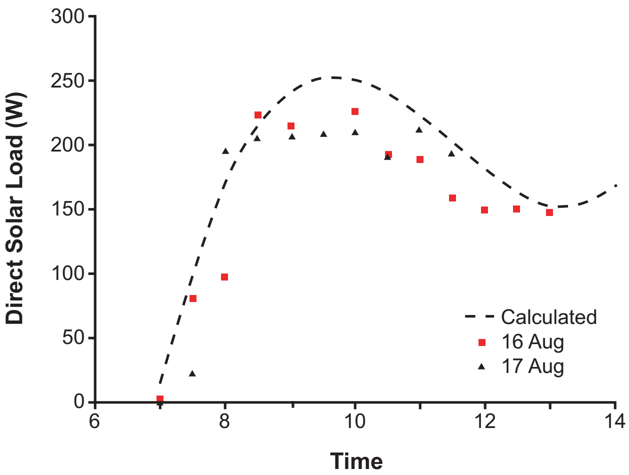


Fig. 8-1. Solar load ($\dot{Q}_s$) for direct solar radiation for a standing figure without clothing ($\alpha = 0.68$). Because of the interaction of solar intensity and solar angle, the maximum $\dot{Q}_s$ does not coincide with the maximum solar intensity, but does at the optimum combination of surface area exposure and solar intensity. Discrete values were based on measurements of incoming solar radiation at Fort Bliss, Texas. Calculated values were derived using input values from a solar radiation model.

Whether or not radiation is absorbed, reflected, or transmitted depends on the physical properties of the surface. The absorptivity (α) of a surface determines the absorption of radiant solar energy in the visible spectrum, whereas emissivity (ε) determines the absorption and emission of thermal radiation. Because α refers to the visible range, color and surface texture are also factors. In the IR range, texture is the primary clue to (ε) properties.

Under most circumstances, the meteorological information required to separate incoming radiation into the incoming solar and IR components is not available. Instead, values for the effective radiant field (R_e) and mean radiant temperature (T_r) are estimated. The assumption behind these two terms is that the radiant load is distributed equally over the body. The effective radiant field (R_e) is the total radiant energy exchange in an imaginary isothermal black enclosure at T_r if body surface temperature ($\overline{T}_s$) equals T_a.[14] h_r is the radiant heat transfer coefficient.

(15) $R_e = h_r \bullet (\overline{T}_r - T_a)$ [W • m^{-2}].

As discussed in the instrumentation section, T_r can be measured with a relatively simple instrument: the black globe thermometer. The globe thermometer essentially integrates radiation into a single net value. In contrast, attempting to sum the radiation term (R) from six or more separate components is much more complex. The concept of T_r is widely accepted by physiologists, but might present some problems in outdoor environments where the solar load is a more significant factor in the thermal environment. The radiative heat transfer coefficient (h_r) may be derived from the Stefan-Boltzmann law:

(16) $h_r = 4 \bullet (A_r/A_D) \bullet \sigma \bullet \varepsilon \bullet [(\overline{T}_s + \overline{T}_r)/2 + 273.2]^3$ [nude, W • m^{-2} • K^{-1}]

(17) $h_r = 4 \bullet (A_r/A_D) \bullet \sigma \bullet \varepsilon \bullet f_{cl} \bullet [(\overline{T}_s + \overline{T}_r)/2 + 273.2]^3$ [clothed, W • m^{-2} • K^{-1}].

The ratio of radiated surface area (A_r) to A_D is approximately 0.71 for a seated or standing individual.[24,25] The surface temperature ($\overline{T}_s$) may be the mean skin temperature ($\overline{T}_{sk}$) for the nude condition or the mean clothing surface temperature ($\overline{T}_{cl}$) for a clothed individual. The Stefan-Boltzmann constant (σ) and emissivity (ε) were introduced earlier. An additional term, the ratio of the outer clothed surface area to the skin surface area (f_{cl}), is introduced into the equation to adjust for an increase in surface area if clothing is worn.[14] In parallel with the cooling efficiency factor (F_{cl}), the clothing area factor (f_{cl}) is 1 without clothing. If a calculated or direct measurement value is available for R_g, ($\overline{T}_r$) can be approximated by adding a fixed value to $\overline{T}_a$ using an equation developed by Matthew and colleagues.[26] As long-wave radiation varies with $\overline{T}_{grd}$ and $\overline{T}_{sky}$ temperatures, the equation is adjusted for different values of $\overline{T}_a$. A rougher approximation based on assumptions regarding the range of R_g values is no sun ($[\overline{T}_r] = \overline{T}_a$), overcast or cloudy ($[\overline{T}_r] = \overline{T}_a + 20$), partially cloudy ($[\overline{T}_r] = \overline{T}_a + 35$), and clear sky ($[\overline{T}_r] = \overline{T}_a + 50$).[26]

The relationship between the net radiation heat exchange (R) is derived from R_e, T_{sk}, and h_r by the equation[14]:

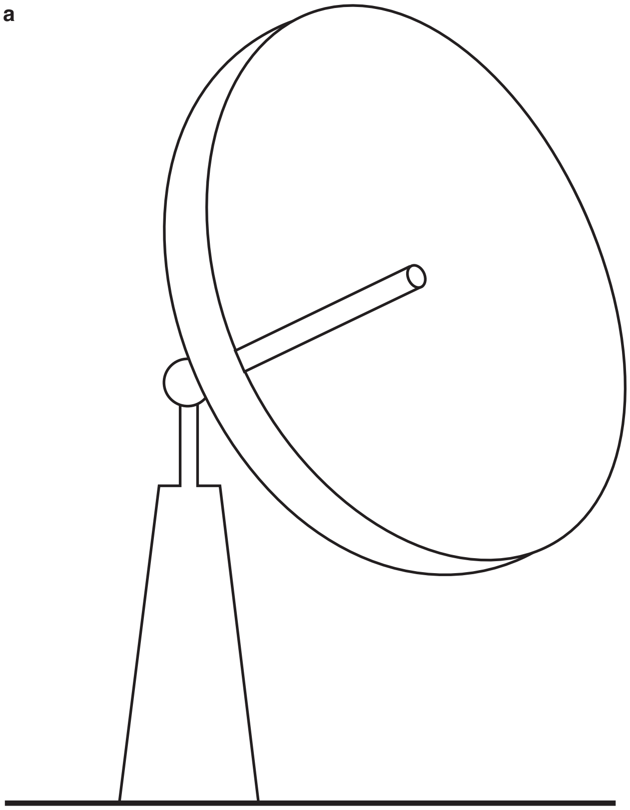
(18) $R = R_e + h_r\,(T_a - \overline{T}_{sk})$ [nude, W • m^{-2}].

If clothing is worn, the cooling efficiency factor (F_{cl}) is added to the equation:

(19) $R = F_{cl} R_e + h_r F_{cl}\,(T_a - \overline{T}_{sk})$ [clothed, W • m^{-2}].

One interesting point is that wearing clothing significantly reduces the solar load[22,27] by insulating the body from external radiation. Relative to heat transfer by evaporation, the solar load would seem to be unimportant. However, as noted by Lotens and Pieters,[28] when the body's thermal state is at a critical level, even a relatively small change in the solar load can be an important factor. In adjusting the original Givoni-Goldman heat strain model, Shapiro et al[29] and Moran et al[30] essentially make that point.

a



b

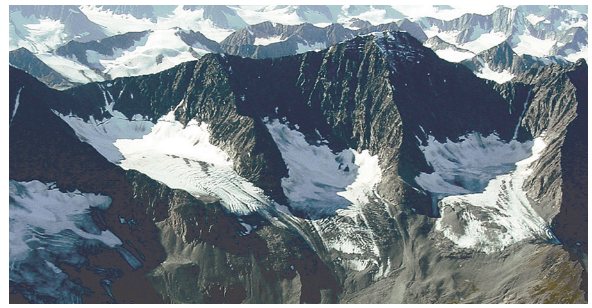


Fig. 8-2. Comparison of (**a**) solar collector to (**b**) alpine cirques, depressions that can act as natural solar collectors. These alpine cirques are several retreating, unnamed, small valley glaciers and several recently deglacierized cirques and ridges north of the terminus of Tonsina Glacier, north central Chugach Mountains, Alaska. Much of the ice disappeared during the last few decades of the 20th century.
Illustration: Reproduced with permission from AMETEK, Inc (Radnor, Pa).
Photograph: Courtesy of Bruce F. Molnia, US Geological Survey. Available at: http://www.usgs.gov/images/topical/glaciers/dsc00053.jpg.

Insensible Heat Exchange

The evaporation of sweat is potentially the most effective physiological mechanism for transferring heat from the body to the environment. When a favorable water vapor pressure gradient exists, evaporative heat loss is the dominant mechanism for maintaining thermal balance. Above an air temperature of 35°C, evaporation is the only effective physiological mechanism for heat loss.[27] During military build-ups, when personnel are abruptly introduced into thermally stressful environments, an important objective is the physiological adjustment of thermoregulatory mechanisms. The acclimatization process, which is also important during basic training of new personnel in warmer climates, is characterized by a more rapid onset of sweating. An acclimatized individual activates thermoregulatory sweating at a lower threshold or set point, which in turn reduces heat storage (S) and minimizes the increase in T_b.

Adolph[27] cited a maximum verifiable sweat rate of 1.7 l • h^{-1}, but indicated that the actual maximum sweat rate was 3.5 l • h^{-1}. Clark and colleagues[3] cite maximum and sustained sweat production levels of 2.1 l • h^{-1} and 0.9 l • h^{-1}, respectively. The latent heat of vaporization for sweat is 2.43 kJ • g^{-1}, which would result in a maximum cooling potential of 1,215 W and 608 W, respectively.

The driving force for evaporative heat exchange is the water vapor pressure gradient from the skin to the environment.

$$(20)\quad E = \omega \bullet h_e \bullet (P_{s,sk} - P_w)\ [\mathrm{W} \bullet \mathrm{m}^{-2}].$$

Skin-wettedness (ω) is the ratio of the skin area completely covered by sweat to total skin surface area. Values for ω range from 0.06 (no active sweat) to 1.0.[1] Many thermal models assume that, for an acclimatized individual, skin-wettedness is 100% (ω = 1.0). Saturated water vapor pressure (P_s) can be obtained from a table or calculated for air temperature range from 0°C to 60°C using Antoine's equation[14]:

$$(21)\quad P_s = \exp^{(16.6536 - [4030.183/(t - 235)])}\ [\mathrm{kPa}].$$

P_a can be derived, for a given T_a, from the saturated vapor pressure (P_s) and ambient relative humidity. For example, at 25°C and 70% relative humidity, P_s is 3.0 kPa and P_a is 70% of that value, or 2.1 kPa. If the convective heat transfer coefficient (h_c) is known or calculated from wind speed and air temperature, the evaporative heat transfer coefficient (h_e) is usually derived using the Lewis relationship (LR).[31] At sea level, LR is the ratio between evaporative (h_e) and convective (h_c) heat transfer coefficients (LR = h_e / h_c).

(22) $h_e = \text{LR} \bullet h_c$ [W • m^{-2} • kPa^{-1}].

For air, LR is a constant value (16.5 K • kPa^{-1}). Evaporative heat transfer is analogous to convective heat transfer, except that the driving force is the difference in water vapor pressure rather than a temperature gradient, thus the concept of a drying or desiccating wind. LR is called an analogy because the theoretical basis for the relationship is not sound. However, the only practical alternative to computing h_e using h_c or environmental parameters and the LR is to derive the coefficient from experimental data.

Although in unusual circumstances moisture can condense on body surfaces, evaporative heat exchange is primarily a pathway for net heat loss from the body surface to the environment. When clothing is worn, water evaporated from the skin surface can condense in the clothing, a form of heat regain, as the heat of vaporization is released in the clothing layer. However, regain in clothing represents a disruption of evaporative heat loss from the body rather than a net gain of heat from the environment, and it is possible for some of the regain to be lost by either radiation, convection, and reevaporation from the clothing to the environment.

Considerable effort has been expended on the preparation of psychrometric charts that demonstrate the thermodynamic relationship between air temperature and humidity parameters, such as wet bulb or dew-point temperature to relative humidity or water vapor pressure[32] (Figure 8-3). Typically, the horizontal axis is air temperature, the top curve represents a saturation temperature (dew-point or wet bulb temperature at saturation), and the vertical axis is an expression of the moisture content of the air (water vapor pressure or density, relative humidity, or multiple scales). These

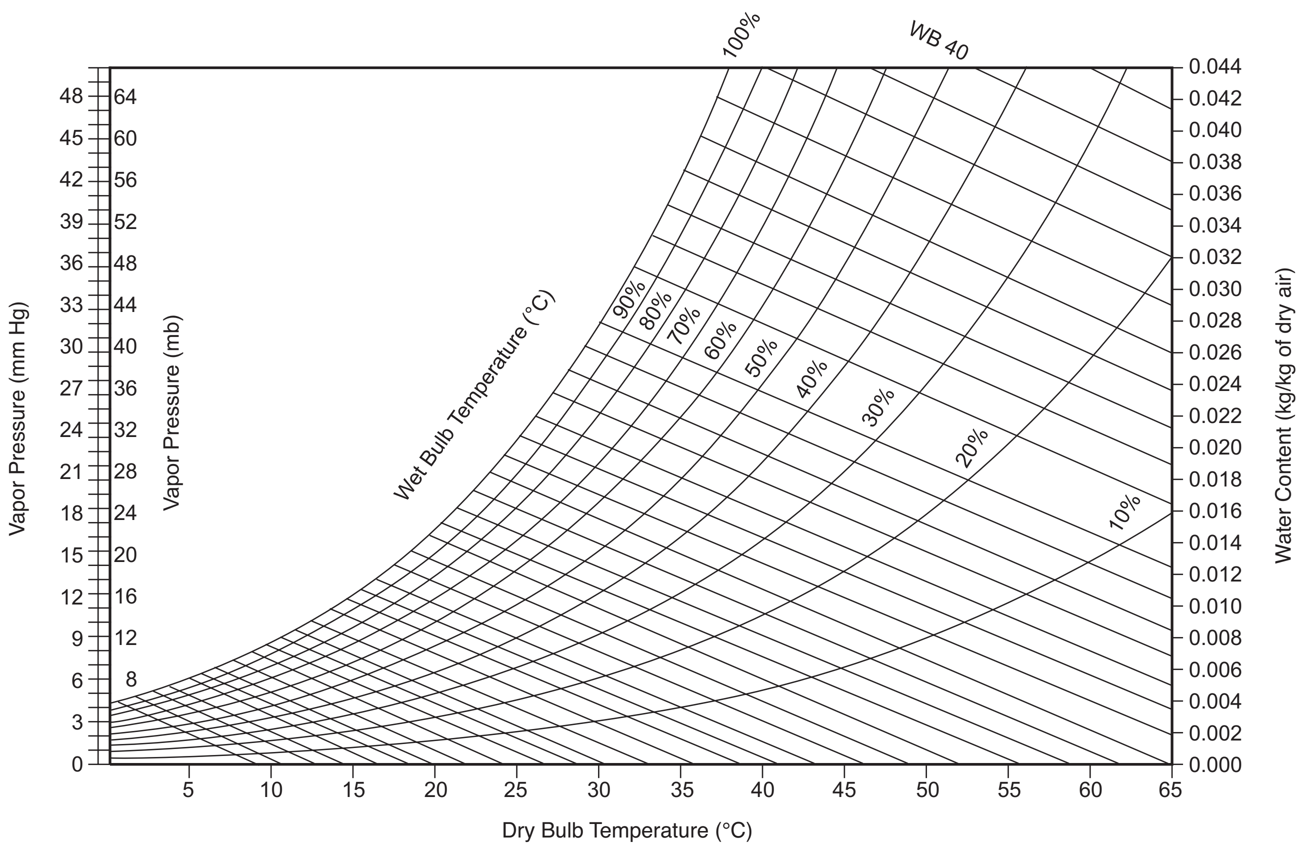


Fig. 8-3. Basic psychrometric chart (barometric pressure 1,000 mb [750 mm Hg]) illustrating the relationship between temperature and different measurements of humidity. If temperature is known, most humidity measurements can be converted into other formats. WB: wet bulb.
Illustration: Adapted with permission from Ellis FP, Smith FE, Walters JD. Measurement of environmental warmth in SI units. *Br J Ind Med.* 1972;29:361–377.

charts provide a valuable illustration of the thermodynamic relationship between air temperature and the capacity to retain water vapor. More elaborate psychrometric charts can be used to illustrate graphically the heat balance equation.[33] Some models used to predict heat strain are constructed as modified psychrometric charts or nomograms.[34,35] From a practical perspective, attempting to use a page-sized chart to obtain more than an estimate of psychrometric relationships is sometimes difficult.

Other Factors

Common vs Special Environmental Factors

The four basic pathways for heat exchange and measurement of environmental parameters determine the potential thermal stress in a specific environment. These basic relationships exist regardless of the branch of service, task, or specific environment. What can vary between environments is the relative importance of each pathway. The same basic meteorological parameters still define that potential for energy exchange; but, in some environments, the importance or mix of factors varies. There cannot be, for example, any significant evaporative heat loss to the environment unless there is a favorable water vapor pressure gradient. If the air is saturated at 100% relative humidity for a given T_a, the ambient pressure (P_a) is equal to the saturated pressure (P_s), and if $T_a \approx \overline{T}_{sk}$, the pressure gradient (ΔP) is greatly reduced, and there will be little or no evaporative heat loss even if the skin surface is completely wetted $(\omega = 1.0)$. However, if $\overline{T}_{sk} > T_a$, the vapor pressure at the skin surface will be greater than the ambient P_a, regardless of the relative humidity, and evaporative heat loss can occur. Base security personnel (regardless of their branch of service), who perform similar duties, are usually exposed to similar environments. Base security personnel normally operate in "built environments," where hardtop road surfaces and buildings are common features of the environment. However, to provide security at more remote sites on a base, a military security unit can work more like a combat patrol, either from vehicles or on the ground. What can vary between environments are special conditions (eg, proximity to airstrips, large hangars, or other maintenance buildings) that are neither outdoor nor normal building interiors. Even more varied are the vehicles, ships, and aircraft operated by even one service branch. Ships, for example, are basically metal islands that shift orientation and position. Except on minesweepers, the metal on ships increases the potential for conduction and reflected or emitted radiation.

Pressure

At low elevations, atmospheric pressure is measured primarily to correct other meteorological values relative to standard temperature and pressure conditions. At higher elevations, reduced pressure has an important effect on oxygen saturation curves. Consequently, atmospheric pressure is a more critical environmental parameter in alpine environments. In terms of heat exchange, as atmospheric pressure decreases, air density and convection heat loss decline. The reverse occurs with evaporative heat transfer: as pressure decreases, the potential for evaporative heat transfer increases. Adjustments for the effect of reduced pressure on convective and evaporative heat transfer coefficients are usually presented as exponential equations,[14] although Chang and Gonzalez[36] have suggested a linear relationship. Barometric pressure is also used to predict changes in weather from movement of high- and low-pressure air masses.

Precipitation

Rain. There is no doubt that standing in cold shower water will cause rapid heat loss. Conversely, to rewarm an individual, a hot shower is nearly as effective as immersion. However, under normal circumstances, military personnel caught in the rain are clothed, and the duration of the exposure is usually relatively short. The thermal consequences of exposure to rain thus depend on the prevailing air temperature and the extent to which insulation has been reduced by water saturation. The probability of an adverse effect increases with the amount and frequency of rainfall, but quantifying the amount of rain has limited value in predicting any direct effect.

Snow. Although direct contact of exposed skin to snow results in rapid heat loss through the melting process (the skin gives up 79 calories of heat for each gram of snow melted), most of the skin area is covered. The more important indirect effect of snow is the progressive wetting of clothing and the consequent reduction in insulation qualities. The Extended Cold Weather Clothing System incorporates a breathable, water-resistant membrane in the outer shell garments to minimize that problem. In extreme cold, snow is less likely to melt on clothing surfaces, so there is less need for water repellency. Deep snow and frozen ground increase the potential for cold injury. Snow varies in moisture content and structure, and those characteristics may change over time in response to wind and temperature. The potential danger presented by snow depends on the interaction between air temperature and snow. When melting snow soaks into clothing, cold injuries can occur even when air temperatures are well above 0°C.

Temperature of Bodies of Water

Although water is not a standard weather data element, in training or operational settings, tactical movement can require partial or near complete immersion in littoral ocean water, lakes, ponds, swamps, marshes, streams, and rivers. Factors that influence the thermal effect of water immersion are duration, depth of immersion (eg, feet, knees, and torso), water temperature, and flow rate. For water or any fluid, temperature differences are the driving force for convective transfer. Water temperatures can be stratified; thus, it might be valuable initially to measure a vertical profile of water temperatures over the range of exposure depths.

A particularly difficult topic to assess is partial immersion. The 1996 deaths of Rangers in training were probably attributable to hypothermia in the aftermath of partial immersion. Marine and SEAL (SEa, Air, and Land) units frequently operate in the coastal environment where partial and periodic immersions are normal requirements of their duties. Flooding and stream crossings can make immersion a factor in desert operations as well.

Meteorological Parameters

Meteorological measurements that define the thermal environment are (*a*) temperature, including ground and air temperatures; (*b*) wind speed and direction; (*c*) humidity; and (*d*) the separate components of radiation, including solar (direct, diffuse, and reflected) and IR (sky and ground) parameters. Other relevant influences may include other surface temperatures, such as tools, fuel pump handles, armored vehicle surfaces, and asphalt. An awareness of diurnal and seasonal cycle variations is also important. Some cycles, such as solar radiation, are obvious. Other less apparent cycles include (*a*) the different lags in response time between ground and air temperature, (*b*) the skewed distribution of air temperature because of a combination of sunlight and ground warming, (*c*) temperature-related variation in relative humidity, and (*d*) less predictable diurnal variations in wind speed and direction.

MEASUREMENTS

There are many ways to measure the four basic heat transfer parameters. Factors that determine how measurements are made include the following: (*a*) complexity of the environment, (*b*) meteorological scale, (*c*) measurement objectives, (*d*) individual parameter measurements, (*e*) other meteorological parameters, and (*f*) stations and instrument packages.

Complexity of the Environment

Local conditions can significantly alter each of the four basic heat transfer parameters. It is important to measure parameters at the operational site. In addition, measurements should be appropriate to the tasks or activities. Normally, air temperature is measured near the center of mass or head level. However, in some environments, especially deserts, the vertical temperature profile can be extreme. The air temperature at head level may be in the 40s (Centigrade), whereas at ground level it can be in excess of 55°C. The thermal stress experienced by a prone rifleman will be underpredicted on the basis of a measurement taken at a standard height. If defensive earthworks are used, even subsurface temperatures can be important. The presence of overhead vegetation, cloud cover, large bodies of water, or rock might affect the daily temperature distribution pattern.

Wind is channeled by topographic features. Surface roughness or vegetation affects airflow patterns in a vertical profile analogous to the temperature profile. There are also daily patterns of air movement associated with large bodies of water and upslope and downslope air drainages. Cold air drainage can be of particular importance in alpine regions.

The site exposure relative to the position of the sun is important when solar radiation is considered. A field position on the military crest of a south-facing slope will receive significantly more solar radiation than a similar position with a northern exposure. Certain surfaces (eg, sand or snow) have high surface reflectance or albedo, which affects local radiation levels. Sunburn and eyestrain can also result, but those effects are not thermal effects in terms of heat exchange. Cloud cover significantly alters the characteristics of radiation, as will various types of overhead cover (Figure 8-4). Air moisture content also displays a vertical profile and is affected by movements of air masses, local precipitation or surface water, and vegetation.

In planning operations from a remote site, it is useful to recognize that climatic data can be mean values that were measured at sites favorable to human habitation. An average relative humidity of 50% does not guarantee that periods of extreme humidity cannot occur. Humidity will vary with the movement of different air masses through an area or even with changes in wind direction. The diurnal cycle of air temperature is mirrored by the variation in relative humidity. When air temperatures are typically lowest just before sunrise, relative humidity is often at the daily high (Figure 8-5). Monthly mean air temperatures might obscure an extreme range in both daily temperatures and between days. Rain on cold days can also have a short-term effect on heat exchange, even with waterproof clothing; but, it is generally treated as insignificant short-term phenomena when analyzing the thermal environment.

Site Heterogeneity (*Landscape*)

In an attempt to integrate ecology with other cultural and economic factors, a new discipline called "landscape" emerged in the 1980s. One of the useful elements of landscape was the basic premise that the environment was a physical mosaic of patches, rather than a homogeneous state, and that target populations moved within that mosaic.[37] This concept of heterogeneity or patchiness succinctly delineates the basic problem in applying laboratory models to the field environment. The real world is often not a good laboratory because the environment and interactions within the environment are too complex. Landscape methods were developed to apply models to a patchy environment. A relatively simple method is to identify and measure characteristic regions or zones within the total environment and then do a time-space study to determine when and how long each zone is occupied. The International Organization for Standardization, in Standard 7933,[38] suggests such a weighting procedure to accommodate workers who move between thermal environments.[39] Each zone or microenvironment might display cyclical behavior, such as diurnal or seasonal variability. Site-specific features include the following:

- north-south facing slopes,
- leeward-windward sides of an island,
- vegetation,
- road surfaces,
- hanging troughs or cirques (mountains),
- depressions or hollows
- elevated terrain,
- land-sea breezes,
- upslope and downslope winds, and
- lower air temperatures associated with bogs and other wetlands.

Urban Environments

The focus on thermal environments tends to be either large-scale, remote field sites or indoor urban locations. One of the most complex environments for military operations is an urban area, either damaged or intact. All the thermal elements of a natural environment are present, but the urban topography is complex. A notable feature is wind channeling,

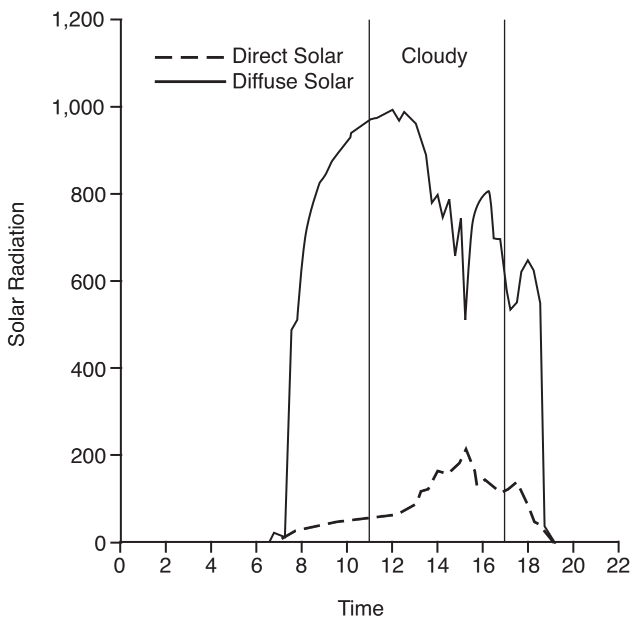


Fig. 8-4. Effect of cloud cover on direct and diffuse solar radiation measured at the US Marine Corps Mountain Warfare Training Center, California, on September 9, 1994, as demonstrated by comparison of clear and cloudy portions of plot.

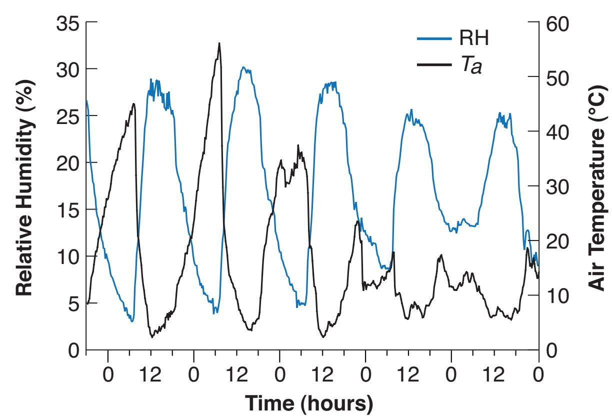


Fig. 8-5. Demonstration of the relationship between measurements of air temperature (T_a) and relative humidity (RH). When air temperatures reach the daily maximum because of increased moisture capacity or saturation level, relative humidity is minimal. The situation is reversed at the morning minimum temperatures. Measurements were taken at the US Marine Corps Mountain Warfare Training Center, California, on September 4–8, 1994.

because winds are compressed and funneled between buildings as they would be in a natural canyon. Another canyon feature is the difference between north- and south-facing solar exposures. Relative to a position on earth, the sun travels an east-to-west pattern, reaching its zenith in the northern hemisphere, directly south of a site. Areas with moderately tall buildings on streets running north-south often have a definite shift throughout the day between shady and sunny areas of the street. Initially, direct solar radiation will strike buildings on the west side of the street, leaving the east side in the shade; but, as the sun rises and moves from east to south, the entire street is illuminated by the high, southern sun. As the sun sets to the west, the west side of the street is cast into the shadows, and the east side now receives most of the available direct solar radiation. A combination of tall buildings and a low winter sun can result in very little solar radiation or light reaching the streets. On a smaller scale, trees along a street can cause a pattern of alternating shade and sun-warmed patches; variations in surface texture can also contribute to the complexity of the urban environment. Asphalt heats rapidly because of solar radiation, whereas a smooth concrete surface can reflect radiation and heat less rapidly. A grassy surface will be cooler, and shrubs might break up strong direct winds and create more turbulence.

Interior Environments

The distinctions between outdoor or field environments and those inside buildings can vary in the relative importance of different environmental parameters, but the same four parameters still determine the thermal environment. Building interiors cover an almost infinite variety, ranging from modern high-rise offices to unheated garages and hangars. In a closed, climate-controlled building, thermal conditions are often referred to by room temperature, despite the contribution of the other parameters, because all four parameters are essentially constant at a given temperature setting.

A building with climate control (eg, heating, ventilation, and air conditioning) is generally not an extreme environment. Inside most buildings, the intensity of activities and the associated metabolic heat production is often in a narrow, relatively low range. Individuals can be uncomfortable, and this might adversely affect performance or morale, but environmental conditions are less likely to have an acute effect on health. Occupants of an office building have several options to adjust to an uncomfortable climate, including altering heat flow, ventilation, and air-conditioning, or adjusting clothing when humidity is low enough to allow some evaporative loss.

A modern building without climate control—as can happen as a result of a massive power failure, catastrophic weather events, or warfare—is quite another situation. The heat balance of an unheated building is similar to that of the human body without any metabolic heat production and greatly reduced evaporation. The lag between external conditions and a significant change in interior temperatures is sometimes attributed to thermal inertia. Changes in temperature are slow because of the large mass of the building and the rate of heat transfer at the building surface.

When the mass of the building reaches a low, even temperature with the mass of the walls and building contents at a uniform temperature, the building may be termed "cold-soaked." Confounding factors include external heat sources (eg, solar radiation) or poor insulation provided by a large glass expanse. A temperature difference in the opposite direction will obviously reverse the direction of the net heat exchange, and the building will become "heat soaked." However, the basic principles are the same.

Buildings are difficult environments to assess because a building is an ensemble of separate microscale environments, often with asymmetrical elements. The combination of doorways, windows, climate control, and furniture may be unique. Often, interior spaces must be quantified on a smaller scale (ie, each desk and occupant). The same basic rules apply, but asymmetry and smaller scale variability make it a more difficult process. Windows and point heat sources (eg, radiators) produce an uneven exposure to radiant sources. McIntyre[25] has emphasized that asymmetry can contribute to a sense of discomfort. Major radiant sources (eg, ship engines) also contribute to asymmetry. Electronic office equipment can be another heat source. To evaluate an indoor thermal environment, an IR scan can be useful in pinpointing asymmetry of radiation sources, including sources and sinks in the windows and walls. The building interior is spatially complex, so drafts can be detected best with a handheld electronic anemometer, which is sensitive to low air movement and can be easily used at different heights and small spaces (eg, underneath desks).

A factor that is not directly related to the thermal environment is clothing. The amount of clothing worn and its distribution on the body can vary significantly, but building climate control systems are based on the presumption of a certain level of clothing insulation. It can be unfashionable or it can violate dress codes to match the building thermal environment. For example, military personnel must often conform to specific guidance regarding clothing. It is difficult to conform to a common clothing standard in a building with a variable set of building microclimates. Of course, activity level, age, and body mass are also factors that can dictate differences in dress.

Nonurban Environments

Environments with gentle topography and open, low vegetation (eg, plains, farmland, open marshes, and open deserts) offer relatively simple landscapes, whereas the topography and orientation of mountains and canyons clearly parallel the complexity of the urban environment. Just as navigation by Global Positioning Satellites is sometimes blocked in mountains, canyons, or a city, wind and solar radiation are blocked or channeled by broken topography. Airflow can follow distinct daily upslope and downslope patterns in the mountains as cold, denser air flows down and warmer air rises from the valley and basin floors. Winds can also be channeled through canyons or ravines so that velocity and direction vary with topography. In areas with large bodies of water, the daily variation in onshore and offshore winds is also a factor.

On a finer scale, broken terrain or vegetation creates air turbulence as the smoothly flowing upper air contacts boulder fields or patches of tall and short vegetation. There are often distinct differences in vegetation on canyons and slopes that are orientated north and south, because the variation in solar radiation affects temperature and soil moisture. In high mountain ranges, the leeward side of mountains can receive significantly less moisture than the windward side. These phenomena are particularly well known in the western United States, where the drier eastern side of the ranges is said to be in a "rain shadow." Heavy or patchy vegetation also creates a complex landscape. Extreme cases include the infamous triple canopy forests of Southeast Asia.

Military Interior Environments

The interiors of armored vehicles, helicopters, and different fixed-wing aircraft (eg, fighters, high-altitude bombers, tankers, cargo planes, and other forms of air transport) are all unique environments. Human factors, including the potential for thermal stress, are a design element for each of these mobile environments. The actual or resultant environment can be a product of external meteorology, the parameters and physical properties of the vehicle (eg, mass, material properties, and color), internal heat sources (engines), climate control, and the metabolic heat production of the crews. In considering just the thermal environment of an armored vehicle, the vehicle's interior environment could be modified by (*a*) varying the amount of exposure to solar radiation from full exposure to full shade, (*b*) either opening or completely buttoning down hatches, (*c*) turning the engine on or off, and (*d*) noting the presence or absence of crew members. Each of those conditions can vary, depending on the tactical situation, concerns over acoustic or thermal image, and other such situations.

Meteorological Scale

The area of operation for a military unit varies with the unit's level of organization. A progression from platoon to corps or army level encompasses a larger and larger area. In terms of meteorology, the scale of concern expands in a similar manner. Macroscale or synoptic meteorology considers the general distribution of air masses and pressure over a large area (eg, an entire theater of operation). The general weather maps of the United States and Europe showing air masses, pressure isobars, and other data are macroscale or synoptic weather maps. The primary focus of synoptic weather is areas of high or low pressure, general wind patterns, and the movement of large air masses or fronts. The clearest images of synoptic patterns are obtained via satellites or other remote sensing systems. The time scale for synoptic weather might be in days or weeks.

General weather patterns reflect the trends in longer term forecasts, but synoptic patterns often cannot adequately forecast the weather that will be experienced by an individual or unit operating within a relatively smaller area. Synoptic weather indicates the general trends or conditions or potential for weather events (eg, the percentage of probability of local precipitation), but it does not provide adequate or sufficient information for local or immediate conditions.

Mesoscale meteorology concerns local weather patterns on a time scale of minutes to days. As a weather front moves through an area, the distribution of local winds—the dominant mesoscale feature—determines the local weather events that affect individuals and small units. The local weather radar, often presented with television weather reports, is concerned with mesoscale weather.

The dividing line between mesoscale and microscale weather is not entirely clear. The weather that individuals experience directly is microscale weather. Some meteorologists consider local variations in wind patterns (eg, upslope or onshore winds caused by local topographic or geographic differences) to be microscale events. Other meteorologists, perhaps depending on the area or scale of the effect, can see the same phenomena as a mesoscale event.

EXHIBIT 8-2

OPERATION OVERLORD

The decision to proceed with the Normandy invasion on June 6, 1944 illustrates the interaction of climatic data and weather forecasting. During World War II, from the Russo-Finnish War (1939–1940) to the Battle of the Bulge in the Ardennes (1945), weather was both a strategic and personal factor that separated victory and defeat, although it had more to do with the strategic concerns than individual physiology.

The information in the following account is based on official military histories by Harrison[(1)] and Pogue.[(2)] Unless otherwise indicated, both sources present the same information in approximately the same detail. The two sources focus on the requisite conditions for the invasion and the events leading to the final decision to commit forces on June 6. There is no direct indication that the physiological effects of water or air temperatures were a factor in selecting D-Day. There is some indication of concern that fall and winter conditions might impend later operations. Harrison[(1)] stated in reference to delaying the invasion until June 19 that " . . . the longer the postponement, the shorter the period of good campaign weather on the Continent." However, a more important concern was the difficulty in maintaining secrecy and morale if the invasion was delayed. It should be noted that operational weather concerns generally focus more on mobility and logistical problems than on soldier discomfort or environmental exposure. There is little indication that the effect of weather on individual soldiers was of paramount concern in planning major operations during World War II. Unlike early European and American armies, the armies of modern Europe did not curtail operations and enter winter quarters or camps.

Nonetheless, the selection and progression of the decision to proceed with the Normandy invasion indicate the importance of both long- and short-term meteorology on military planning. The general pattern of climatic trends (eg, rainfall, air temperatures) allows the prediction of a set of meteorological limits or bounds for military operations. The initial planning was for a spring or summer attack. Invasion preparations were to be completed by Y-Day, and a tentative date was set after May 1. This was changed to June 1 to accommodate an enlarged operation.[(2)]

The actual invasion date, D-Day, was to be the earliest possible date after Y-Day. The critical elements were determined to be a combination of daylight and high tides, with a secondary concern for sufficient moonlight to support airborne operations. Daylight was required for naval gunnery observations. The actual invasion would occur within 3 h of high tide, but at least 30 min of daylight was required before the first invasion wave. The projected windows for D-Day could be projected from moon phases and tidal information obtained from nautical almanacs. The earliest window was June 5–7. The next window would begin on June 19.

Climatic information can give an approximation of the anticipated air and water temperatures, and almanacs definitely predict the timing of tides and moon phases. However, no table could accurately predict wind or cloud conditions. Pogue[(2)] states that, "In the last days of May, the Supreme Commander began to watch the weather forecasts very closely. He got in the habit of talking over the reports with the Chief Meteorological Officer . . . so that he understood fully the value of the reports and the basis on which they were made."

The forecast on May 29 was favorable for the following week. D-Day was set for June 5, 1944.[(2)] The two sources defer regarding forecast information through June 3. Weather information remained favorable (the morning of May 3),[(1)] with Pogue[(2)] stating that forecasts were "less hopeful" on May 2, but Harrison[1] stating that Eisenhower described it as "favorable" in a telegram to Washington on May 3. However, by the evening of June 3, inclement and unstable weather was forecast. In addition, because of instability, weather forecasts could not be considered reliable for more than 24 h.[(1)] Despite the unfavorable forecast, some naval elements were initially given orders to proceed.

At 0430 h on June 4, the forecast indicated low, overcast conditions for June 5, which would limit vital air support. The operation was delayed for 24 h until June 6. A new forecast, presented at 2130, indicated a new weather front and a break in the weather. Conditions would be adequate for overnight bombing and naval gunnery on the morning of June 6. Wind speeds would decrease later in the morning. The final decision was made at 2145 on June 4,[(1)] a little more than 24 h before operations. Another weather briefing, at midnight—which would have allowed a delay of the operation, but would not allow sufficient time to reschedule the operation for the following day—provided no new information.[(1)] At 0330 on June 5, weather was bad, but the forecast made at 0200 on June 5 indicated a 36-h break, but could not forecast further.[(2)]

(**Exhibit 8-2** *continues*)

Exhibit 8-2 *continued*

The historical record indicates that the forecast was accurate, and the invasion proceeded as planned. When the next invasion window (June 19) arrived, a storm effectively closed Omaha Beach until June 23 and severely damaged the artificial harbors that were crucial during the early stages of the invasion. A later June landing would have been unsuccessful. Had the Allied forces not invaded on June 6, the course of World War II might have been significantly different. Although it is of limited value to speculate on alternative outcomes, without a successful June invasion, the German military might have been able to concentrate successfully their efforts against the Russian forces, or the Russians might have defeated the German forces in the absence of any Western allies.

The decisions regarding the timing of the Normandy invasion illustrate a progression from broad climatic considerations to a narrower time frame with increasing forecast accuracy. The initial selection of Y-Day was concerned mostly with military readiness (eg, when was the earliest possible date for a summer invasion?). It is also important to note that the final decision was a human one, with the responsibility ultimately resting on the Commander's shoulders.

Data sources: (1) Harrison GA. *United States Army in World War II: The European Theater of Operations: Cross-channel Attack*. Washington, DC: Office of Military History, Department of the Army; 1951. (2) Pogue FC. *The Supreme Command*. Washington, DC: Office of Military History, Department of the Army; 1954.

Onshore and offshore winds are mesoscale events for a large island or a long coastline, but they might be a microscale factor for a moderate-sized inland lake. A single point or local ground-based weather station or observer collects only microscale weather data. A time scale suggested for microscale weather[40] of minutes to hours indicates the immediate nature of microscale events.

The different scales are significant in terms of weather forecasts and local thermal environments. It is important to recognize that, as the operational area of a military unit expands, the scope of relevant weather data also expands from local observations and measurements to an ability to predict the range of weather conditions and thermal environments that can be experienced over the entire area of operation. The relevance of the local data to mesoscale or synoptic weather depends on the homogeneity of the local environment and how representative the site is of the larger region.

Measurement Objectives

The collection of meteorological data is dependent on the objectives of the user. Long-range or strategic planning requires different data than planning for a mission with a specific window for execution. As the execution time nears, more and more accurate forecasts are both required and possible. When the mission begins, real-time, ground-level weather data are added to the requirements for forecasts. Specific operations or tasks often have different meteorological requirements. Helicopter pilots generally operate from ground level to 600 m above surface features and can range over a large area, whereas a rifleman occupying a defensive bunker has a much more limited area. Differences that are of no significance to the former can be very important to the latter.

Although not directly related to thermal environment, certainly the drama over General Eisenhower's planning for the Normandy invasion captures the importance of short-term weather forecasts. Long-term data allowed selection of a target zone (time and place), and short-term forecasts determined the decision to commit; however, only real-time data determined what conditions existed when the troops landed on the beaches (Exhibit 8-2).

Whether planning for another Normandy invasion or a peacekeeping mission in the Caribbean, environmental data must be considered in three stages. The first stage is long-term planning during the predeployment phase. Climatic data provide the means to conduct a predeployment reconnaissance of the potential thermal environments. During an ongoing, long-term operation, the same climatic data provide medical support staff with the basis for planning logistics (clothing, water, and special needs), medical treatment (patient load, special medicine or care, staff preparation, transport, or evacuation), and normal seasonal changes that could be anticipated from climatic data. The accuracy of a forecast increases as time approaches real time. A forecast made for the year can predict only general seasonal trends, but the accuracy of the forecast increases as the time frame compresses from month to week to day to hour and as the uncertainties of the preconditions are reduced.

Sources for long-term strategic or predeployment planning consist primarily of climatic data from military and civilian sources, including almanacs, records from US military bases, foreign military sources, military histories, and government and private meteorological services. Limitations of published climatic databases are readily apparent. When US forces were committed to Somalia, the climatic and meteorological data available to most planners were limited to major cities. In Somalia and many other countries, the major urban areas are located along the coast. Little information is available on interior zones. If data consist only of average monthly temperature and precipitation, it is difficult to determine any meaningful information regarding daily extremes, wind speeds, and seasonal transitions that do not conform to the month-by-month calendar divisions. Other data that do not lend themselves to monthly averages include the distribution of precipitation and values for humidity and humidity variability. Day length and estimates of solar load[4,41,42] can be calculated from latitude or almanacs. Even with the preceding guidance, the task of relating solar phenomena to local terrestrial sites is difficult. Computer programs are available for calculating solar time, angle, day length, and other factors.[43] An approximation of conditions can be derived from knowledge of regional or climatic information. Climatic classifications (physical geography or ecology) provide a general framework for understanding the seasonal patterns. Better references include more detailed information (eg, monthly average and absolute extremes for air temperature, relative humidity at morning and midday, and days per month with precipitation).

Long-Term Climatology for Predeployment Reconnaissance and Planning

It is useful to know what weather information is available to the US military. Within the US military, the primary responsibility for meteorological data collection lies with the US Air Force and its meteorological teams. The Air Force Combat Climatological Center (AFCCC) in Asheville, North Carolina, can provide tailored climatological summaries of relevant environmental data for specified regions worldwide. Information on submitting requests for climatological data products can be obtained from the following address: AFCCC/DOO, 151 Patton Avenue, Room 120, Asheville, NC 28801-5002. Using the following Web site, https://notus2.afccc.af.mil (US Air Force Staff Weather Officers [SWOs]) will also provide climatological summaries for their areas of responsibility to interested military users. During ground-based operations, the US Corps of Engineers is an important secondary source for information, because they have knowledge of the significant effect of inclement weather on flooding, road passability, traffic, and construction.

Real-Time or Near Real-Time Data and Forecasts

SWOs and their meteorology teams have the responsibility to provide real-time weather data and forecasts to military users. These SWOs are attached to Army units and operate the Army's Integrated Meteorological System, which is located at separate brigade, division, corps, and echelons above corps headquarters deployed outside the continental United States, and at some continental United States locations. The Integrated Meteorological System[44] provides a broad range of weather information products (including current data and forecasts of local air temperature, humidity, wind speed, and solar radiation), as well as recent weather satellite imagery.

The Headquarters Air Force Weather Agency at Offutt Air Force Base, Nebraska, maintains the capability to provide current satellite and other weather information around the world. This information can be accessed at the following Web site (where it is necessary to register for a password): https://weather.afwa.af.mil/.

Parameter Measurements

Primary Environmental Parameters and Instruments

There are a variety of measurements that can be made to assess the potential impact of the thermal environment on military personnel and their missions. It is important to be aware of the types and limitations of environmental measurements. In addition to providing basic knowledge to assist in any direct effort to collect local weather data, knowledge of weather instruments and measurements will enable an individual to make an informed request for better information from other agencies and sources. Users need to know what information to collect and how to use it.

In principle, measuring air temperature, wind speed, solar radiation, and humidity (the four basic parameters that define the thermal environment) is not difficult to do. However, when more careful consideration is given to instrument type, number of sensors, location, sensor placement and operation, data acquisition, and processing, the process becomes more complex. It is necessary to determine whether or not there is adequate justification of costs in time and other resources to collect meteorological data. In other words, can you get it elsewhere?

The decision to collect weather data directly is dependent, to a large degree, on whether or not available data are adequate or relevant to local needs. The local site conditions and circumstances of reported thermal injuries might be important. Under tactical conditions, ground-based military personnel are often restricted in their choice of environment. An infantry member can be assigned a defensive position and told to defend in place until relieved. Environmental parameters that affect thermal balance can be local, and substantial differences in exposure to sun and wind can be a matter of only a few meters. It is difficult to appreciate how little local weather data are available, even for retrospective analyses. The windchill index[20] only requires T_a and wind speed, yet Whayne and DeBakey[45] were unable to evaluate the significance of windchill on the incidence of cold injuries in World War II from the lack of proximate weather data.

Individuals deployed in military operational settings typically do not have direct access to weather information. Meteorological data and weather effects are considered intelligence issues, and information is provided to those organizational levels that have the ability and capability to use the information. Certainly, in planning an operation, all personnel should be provided with basic information regarding the anticipated weather conditions. However, when one considers an individual member of the infantry assigned to hold an exact position, the utility of weather information may be reduced, because as a member of a military group, his or her individual options can be extremely restricted. It would, for example, be possible to provide thermometers on zipper pulls or even environmental sensor suites to the individual. The question, then, is what can the individual do with the information? Low-ranking personnel without leadership authority might be unable to do much but complain. In contrast, an independent, small-unit leader (whether a noncommissioned officer supervising a platoon loading supplies in a warehouse, a leader in a Special Operations Forces ground unit, or any tactical leader with authority to make independent decisions) can use information on the thermal environment to plan work–rest cycles, to rotate personnel warming shelters, or to incorporate thermal factors into the selection of a position. When civilians select a campsite or site for a solar-heated home, environmental conditions—especially exposure to sun and wind—are part of that decision. If anything, those factors should be more important to military personnel in temporary shelters.

It is unrealistic to expect that a medical unit would attempt to operate a complete weather station. The most basic rule for weather data collection is to keep it simple. In a tactical operation, even a simple weather kit or sensor suite can be difficult to manage. Data collection can be limited to a pocket thermometer hung from a tree branch. Simple, proximate data that are available to an informed, responsible individual become far more valuable than an elaborate system that is inaccessible to the individual. It is also useful to understand what information can be obtained with minimal effort. A field medical officer can tell from a minimum-maximum thermometer if the possibility of frostbite exists, whereas the wet bulb globe temperature (WBGT) index,[46] or more sophisticated models, requires three or four environmental parameters to predict probability of heat injuries.

The primary meteorological measurements are air temperature, humidity, wind speed, and incoming radiation. Other measurements that can be of value include atmospheric pressure, ground temperature, and precipitation. A variety of instruments and sensors for monitoring meteorological conditions are available, from simple analogue pocket instruments to sophisticated electronic sensors. The attachment describes the various options for monitoring the thermal environment, including types and limits of environmental measurements. In addition to any direct effort to collect data, knowledge of weather instruments and measurement will develop one's ability to make an informed request for better information.

Stations and Instrument Packages

As noted, the US Air Force has the primary responsibility for providing weather support (AR 115-10, 2010). In the future, expanded US Air Force and Army weather capabilities, currently under development, may be able to provide detailed local surface weather. However, at present, in areas where the thermal environment has the potential to cause significant injury, the systematic collection of local weather data may be appropriate. Units should utilize existing Army and US Air Force weather assets and expertise whenever possible rather than establish independent weather capabilities; but, it is useful to have a working knowledge of weather equipment and data collection.

For continuous operations at a specific site, a fixed, permanent weather station can supplement data from other sources. Such meteorological data are more often unavailable or insufficient when an operation is mobile. The most effective way to establish a meteorological collection system is to purchase commercial weather instruments as a complete station. This station should include the basic measurements mentioned previously—air temperature, humidity, and wind speed—and, if practical, radiation should also be monitored.

The heart of a commercial station is an electronic data acquisition (DA) system. Instrument signals are received, translated into appropriate units, and displayed or stored for later recovery or transmission.

Fig. 8-6. WeatherPod miniature weather station. The unit provides environmental measurements through communications to a base unit, with Global Positioning Satellite (GPS) locations. The light (1 kg) unit senses and transmits air temperature, relative humidity, barometric pressure, and GPS position. In addition, it incorporates a solar sensor that detects low light (twilight) and approximate solar intensity. Wind speed and direction are measured using a miniaturized sonic anemometer. To avoid drawing attention, the unit has no moving parts. Versions with radio or satellite-linked wireless communications systems are available.
Photograph: Reproduced from the US Army Research Institute of Environmental Medicine (Natick, Mass).

The basic weather station used during our field studies consists of a battery-powered DA system. The sensors include one temperature and humidity sensor inside a shielded mount, a ground temperature sensor, an anemometer (wind gauge), and a wind direction sensor. A pyranometer is used to measure incoming global radiation. On some stations, a 15-cm black globe thermometer was also included. The instruments are mounted on a 2-m steel tripod with an enclosure for the DA system and storage modules. If a lighter tripod is used, the entire station can fit into two large suitcases.

In that system, a portable computer is used to program and download data. Other stations incorporate programming, display, and output elements into the DA system. For studies focused on meteorology, the basic station can be expanded by adding a barometer, more radiation sensors (including a shaded pyranometer and two net radiometers), a second anemometer at another height, and additional air and surface thermometers. This array is supplemented by a separate WBGT sensor suite. On complex terrain, additional stations are deployed.

Simpler home-weather stations that measure the basic air temperature, humidity, and wind parameters are available. The basic DA system displays data and has limited storage and data processing capabilities. The basic system of one home station weighs 1.6 kg and can be linked to a personal computer. Limitations of these far more economical units include accuracy,

Fig. 8-7. Handheld Kestrel 4000 unit.
Photograph: Reproduced with permission from Nielsen-Kellerman (Boothwyn, Pa).

no radiation or ground temperature measurements, the inability to expand instrumentation, less than ideal mounts for the wind indicator, and alternating current power requirements for some systems. The most important concern is an inability to calibrate or recalibrate the instruments. Periodic comparisons to measurements made with handheld instruments can establish the level of confidence that can be assigned to the system. Despite the limitations, these systems are an attractive alternative to no weather data at all. At present, there is a commercially available battery- or solar-powered, miniature weather station that weighs less than 1 kg; has a height of approximately 15 cm; and measures and transmits air temperature, humidity, solar radiation, wind speed and direction, and rainfall (Figure 8-6).[47]

The alternative to a full-scale weather station is handheld instrumentation. The basic measurements have not changed, but the instruments might be less sophisticated. Individual instruments (eg, pocket thermometers) can be purchased. Simple kits—such as a fire weather instrument kit (Case Belt Weather Kit FSN 8465-00-521-3057F)—have a compact psychrometer (wet bulb and dry bulb temperatures), a simple wind gauge, a compass, and other supplies in a belt carrier. The kit was designed for use by ground-based forest firefighters to provide temperature, humidity, and wind data for planning operations and directing aircraft. Similar compact kits exist to measure the WBGT parameters. These kits feature a miniature black globe thermometer.

Some WBGT sensor kits are mounted as a single unit and use a battery-powered system to collect data and calculate the WBGT index. More recently, battery-powered environmental sensor systems to measure air temperature, dew-point or relative humidity, wind speed, and black globe temperature have been developed. A pocket-sized electronic unit—with the ability to make the required measurements, calculate derived parameters (eg, $\overline{T}_r$) and run a sophisticated heat strain model—has been developed and tested.[48] Sensor suite units can be as small as a cigarette pack (9.5 × 6.0 × 3.0 cm) in a folded position and weigh 155 g, with a 9-V battery.[49] Several companies now offer handheld, battery-powered, miniature stations (Figure 8-7) that measure air temperature, humidity, wind speed, and barometric pressure, and can incorporate a Global Positioning Satellite unit or an electronic compass, and thus measure wind direction, but not solar or rain parameters. One such unit was observed hanging from a tree outside a medical clinic, and forward weather observers have been using these units.

LINKING METEOROLOGY TO MODELS AND USERS

The use of thermal models allows planners to utilize scarce resources better and to preserve the fighting power on the battlefield, both of which can be seen as force multipliers. Chapter 2 of this volume describes in depth the basic principles of thermal modeling, and presents both a historic perspective and a detailed description of the suite of thermal models developed by the US Army Research Institute of Environmental Medicine (USARIEM). This section complements Chapter 2 by explaining how weather data and the biophysics of heat exchange are incorporated into models. The examples that follow are based on work done over a 50-year period by Gagge and colleagues at the J. B. Pierce Foundation (New Haven, CT). The basic equations describing the fundamentals of heat exchange developed at the J. B. Pierce Foundation have been adapted into many models, including some USARIEM thermal models.

Operative Temperature

The original concept of operative temperature (T_o) is based on dry heat exchange between the body surface and the environment.[14,50,51] The premise is to calculate a single value, expressed as a temperature, that would account for heat exchange by convection and radiation (C + R), if all temperatures (surfaces and air) were at the same operative temperature. The general equation, assuming no work (W_k) or storage (S), is:

$$(23)\quad M - E = (h_c + h_r)\,(\overline{T}_s - T_o)\ [\mathrm{W} \bullet \mathrm{m}^{-2}].$$

Equation (23) is equal to the dry heat exchange, or R + C. Several equivalent equations for calculating T_o exist,[5] but the basic equation is:

$$(24)\quad T_o = (h_c T_a + \overline{T}_r h_r)/(h_c + h_r)\ \ [^\circ\mathrm{C}].$$

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)[42] describes T_o as the average of $\overline{T}_r$ and T_a, weighted by their respective heat transfer coefficients. To derive the heat transfer coefficients, wind speed (V) and $\overline{T}_r$, or an equivalent radiation term, must be known. T_o is the temperature of a uniform environment, such as an enclosed test chamber with the same wall and air temperatures ($T_a = \overline{T}_r$), where the dry or sensible heat exchange is the same as the actual environment. One problem with T_o is that h_c is dependent on wind speed. To use T_o as a basis for comparison between environments, the variation from wind speed is accommodated by calculating the equivalent T_o for still air.[52] The relationship between T_o and standard operative temperature (T_{so}) is:

(25) $T_{so} = (h/h')T_o + (1 - h/h')\bar{T}_s$ [°C]

and

(26) $h \bullet (\bar{T}_s - T_o) = h' \bullet (\bar{T}_s - T_{so})$ [$W \bullet m^{-2}$].

The coefficient h is the combined heat transfer coefficient for convection and radiation ($h_c + h_r$), and h' is the same combined term, except that h_c is calculated for the standardized still air velocity.[50]

The New Effective Temperature

The new effective temperature[53] (ET*) has been adopted by ASHRAE.[42] ET* is the temperature of a uniform environment, at 50% relative humidity, where the sensible and insensible heat transfer from the skin are the same as in the actual environment. ET* uses the concepts of operative temperature (T_o), mean skin-wettedness ($\bar{\omega}$), i_m, and the Lewis relationship (LR)[31] to calculate a temperature at 50% relative humidity, rather than 100% RH, which is used for T_{soh} and results in an equivalent heat loss from the skin.

(27) $ET^* = T_o + \bar{\omega} \bullet i_m \bullet LR \bullet (P_a - 0.5P_{s,ET^*})$ [°C]

(28) $i_m = R_t/(R_{e,t}\ LR)$ [N.D.]

P_{s,ET^*} is the saturated water vapor pressure at ET*. LR is the ratio between evaporative (h_e) and convective (h_c) heat transfer coefficients (LR ≈ h_e/h_c). If the convective value (h_c) is known or calculated from wind speed and air temperature, then h_e can be estimated. Values used to calculate the water vapor permeability index (i_m) are the total dry resistance (R_t ($m^2 \bullet K$)/W) and total evaporative resistance ($R_{e,t}$($m^2 \bullet kPa$)/W) from the skin to the environment. Values for i_m index range from 0 to 1.0, with 0 representing an impermeable condition and 1.0 bare skin. Skin-wettedness (ω) ranges from 0.06 (no sweat) to 1.0. As indicated in the *2005 ASHRAE Handbook*,[42] calculation of ET* is relatively complex and dependent on both clothing and metabolic rate. Clothing, activity level, wind speed, $\bar{T}_{sk}$, and mean skin wettedness ($\bar{\omega}$) values are the same in both environments. In Figure 8-8, ET* is plotted as a psychrometric relationship. The plot also incorporates data from Hardy[54] that relates ET* to records of US Army heat-related fatalities in World War II.

Standard ET*[50,55] is a modification analogous to the principle of standard operative temperature. ET* is adjusted to standard or constant reference conditions (sedentary subject in 0.6 clo, air velocity of 0.2–0.5 m • s^{-1}, and 50% relative humidity) to allow better comparisons between environments.

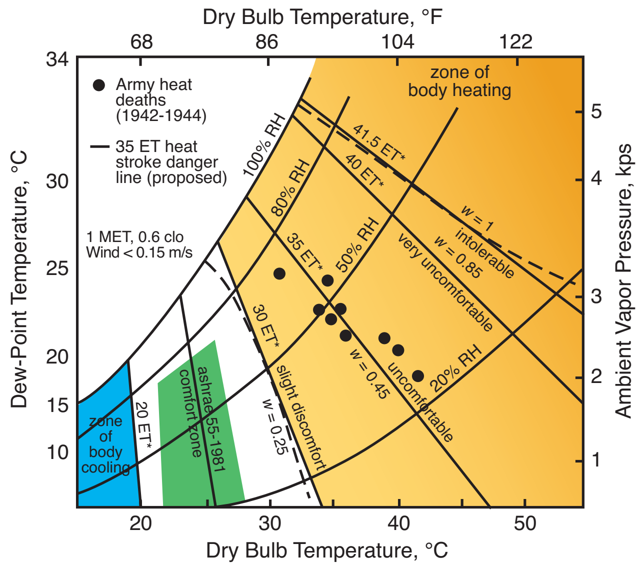


Fig. 8-8. Nomogram for the "new," effective temperature (ET*), including data points for US Army heat deaths provided by Hardy. ashrae: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc; clo: unit of clothing insulation, 1 clo = 0.155 m^2 K/W; MET: unit of metabolism, 1 MET = 58.15 W/m^2. RH: relative humidity.
Illustration: Adapted with permission from ASHRAE. Copyright 2005 © American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc (www.ashrae.org). Reprinted with permission from the *2005 ASHRAE Handbook—Fundamentals*. (This text may not be copied nor distributed in either paper or digital form without ASHRAE's permission.) Data source: Hardy JD. Thermal comfort and health. *ASHRAE J*. 1971;13:43.

Humid Operative Temperature

In a manner similar to ET*, humid operative temperature (T_{oh}) is the temperature at 100% relative humidity that would result in the same heat loss from the skin for a given combination of activity, clothing, wind speed, $\bar{T}_{sk}$, and ω.

(29) $T_{oh} = T_o + \bar{\omega} \bullet i_m \bullet LR \bullet (P_a - P_{s,oh})$ [°C].

The thermodynamic relationship is the same as ET* except for the reference vapor pressure, $P_{s,oh}$, which is the saturated water vapor pressure at T_{oh}. Standard humid operative temperature (T_{soh}) incorporates the still air condition for T_{so} with the concept of T_{oh}, thereby accounting for both sensible and insensible effects.

SUMMARY

To optimize performance during military operations in extreme environments, the military must understand how the environment impacts the soldier. Although many aspects of the physical environment can affect military populations in extreme environments, the factors that influence the thermal state of the soldier—temperature(s), radiation, wind, and humidity—have a pervasive potential to degrade military performance significantly. Thus, the rationale for the military to study how environmental factors influence the thermal state of the human is force conservation by early intervention or prevention of nonbattle injuries, especially among those individuals tasked with difficult missions in the most extreme environments imaginable.

The more these environments and the limits of military capability are understood, the more protective equipment can be improved to prevent environmental casualties, as well as improved medical treatment for individuals who suffer from environmental injuries. This enhances the ability of the military to operate in extreme surroundings and contributes significantly to the vast body of civilian literature concerning environmental extremes. Likewise, collaboration with civilian scientists offers an opportunity for both military and civilians to understand better not only the limits of human endurance, but also the ability of the human body to respond and adapt to environmental stress, and to develop strategies and equipment for minimizing the impact of the thermal environment on human performance, especially during military operations.

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ATTACHMENT: INSTRUMENTS AND METHODS FOR MEASURING PARAMETERS OF THE THERMAL ENVIRONMENT

Air Temperature

The most obvious parameter of the thermal environment is air temperature. It is the factor that provides the drive and direction for convective heat exchange. The most basic thermal environmental monitoring consists of systematically reading a thermometer mounted at a uniform height in a shaded, representative location. A single measurement of air temperature may not be adequate. Air temperature at a given point and time can display a substantial vertical gradient, depending on ground or floor temperature and local air movement. In addition, on complex terrain, there might be diurnal upslope and downslope flows or accumulation of denser, colder air in depressions, and so forth. Choice of the number and location of air temperature sensors is also dependent on the activities of the personnel.

If a multichannel data acquisition station is used with electronic sensors, it is relatively easy to collect additional air temperatures at different heights. Air temperature and other environmental parameters can be quite different for a patient lying on a ground litter and for the standing staff. When possible, the best solution is to monitor air temperature from 0.5 m—from ground level to the maximum occupied height, usually 2 m (Attachment Figure 8-A1).

Air temperature sensors should be shaded from direct sunlight and mounted at a known height. On weather stations, temperature and humidity sensors are placed inside a ventilated enclosure that provides protection from sunlight, wind, precipitation, or physical damage. The standard height for US civilian ground stations is 1.25 to 2 m (4.1–6.6 ft), but weather data collection is highly dependent on the needs of the primary collector. The standard height for wind measurements is 10 m (30 ft). A uniform or standard height might not be entirely appropriate for individuals with differing tasks or work environments. Aviators have different needs than mechanized ground personnel, and theirs—in turn—are distinctly different from those of nonmechanized light infantry. The 10-m height for wind speed measurements reduces uniformity problems related to ground-level turbulence, but it might be a more appropriate measurement for aircraft than ground personnel. The wind speed at 2 m is probably more appropriate for ground personnel. Wet bulb globe temperature (WBGT), which was developed for ground personnel, is measured at 1.2 m (4 ft), which is slightly above the center of mass for a standing person.[1]

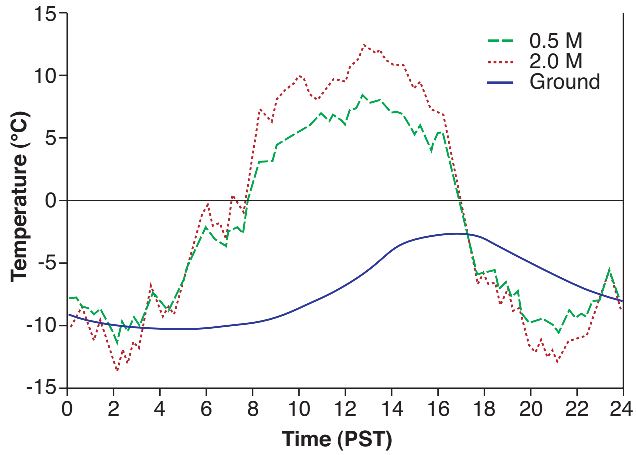

Fig. 8-A1. Comparison of air-to-ground temperatures measured at two heights to ground temperature at the US Marine Corps Mountain Warfare Training Center, California, on January 23, 1988. PST: Pacific Standard Time.

Surface Temperature

Ground temperature is an important factor in situations in which people are in close contact with the ground, especially where the ground is frozen or, as in a desert, where it acts as a significant heat sink or source. In a few situations (eg, when handling metal surfaces that are cold soaked or exposed to extreme heat and solar radiation), there might be some benefit to measuring other surface temperatures. All hot surfaces are also a significant source of radiant energy that may be estimated using the Stefan-Boltzmann equation from the surface temperature. Attachment Figure 8-A2 illustrates the offset between air and ground temperatures at two different locations.

The temperature of anything that comes into prolonged contact with the body surface should be quantified and recorded, although it might not be necessary to monitor most surface temperatures continuously. The temperature of working surfaces or tools can also be important. During extravehicular walks, astronauts have experienced problems with cold tools. Fuel pump handles in cold weather and even a scientist's clipboard during cold chamber studies can cause significant heat loss. The temperature of liquids is also important, whether encountered during military stream crossings, accidental immersions, or accidental spills. Liquids (eg, gasoline or alcohol) can remain liquid well below the freezing point of water. If alcohol stored outdoors at –29°C is spilled on the hands, the combination of extreme cold, the higher convective heat transfer coefficient for liquid, and possibly evaporative heat loss as the alcohol vaporizes can cause local cold injury.

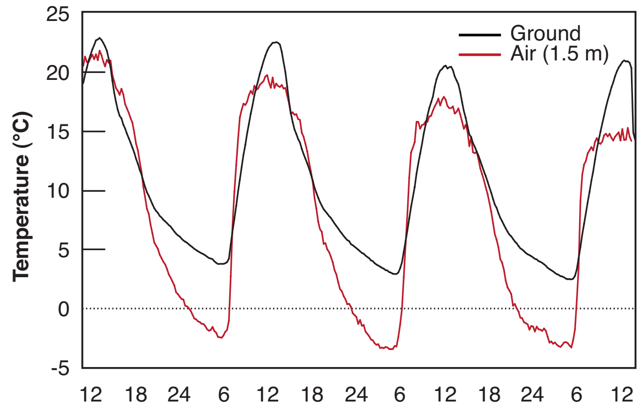

Fig. 8-A2. Demonstration of time lag between ground and air temperatures because of differences in heat transfer and mass in a meadow in the vicinity of the Tuolumne Meadows, Yosemite National Park, September 8–10, 1994.

Temperature Measurement Instruments

Thermometers and other meteorological instruments can be placed into two general categories: (1) relatively simple to use, often handheld instruments based on mechanical or thermal expansion principles; and (2) electronic devices, which are better suited for downloading into data acquisition systems for continuous, real-time monitoring. The operating principle for mercury and alcohol thermometers is based on the uniform thermal expansion properties of the liquids, which also have a favorable range between critical temperatures for freezing and boiling points. Bimetal thermometers are based on the differential thermal expansion of the two metals. Bimetal thermometers are often used for temperatures above normal human tolerances and are more rugged and shock-resistant than liquid thermometers.

Thermocouples and thermistors are solid-state electronic devices that use thermoelectric or electrophysical properties of certain materials to measure temperature. A thermocouple sensor consists of a junction of two dissimilar metals that produces a small voltage, or electromotive force, proportional to the temperature at the junction. This phenomenon is known as the "Seebeck effect." Thermocouple measurement circuits require a second reference junction, at a known temperature, in series with the sensor junction. Thus, the voltage measurement is the net difference in electromotive force between these two junctions, and it is this voltage that is multiplied by the appropriate Seebeck coefficient to produce the temperature reading. Thermistors and resistance temperature devices (RTDs) measure temperature as electrical resistance. Thermistors use a bead of semiconducting material as the sensor. RTD sensors can be fine coils of wire or very thin films of metals (eg, platinum on ceramic substrates). In both cases, calibration tables, curves, or equations for specific thermistors and RTDs are used to convert the resistance values to temperature units. This is usually done online in measuring systems with dedicated microprocessors and readout displays. Thermocouples are smaller, less expensive, and have a wider temperature range than thermistors. However, thermistors are more accurate within their temperature range and are easier to incorporate into general sensor systems because they do not require a reference juncture.

Three useful types of simple instruments are the following: (1) pocket thermometer, (2) minimum-maximum thermometer, and (3) soil (or ground) thermometer. Pocket thermometers are short, glass alcohol instruments that are enclosed inside a protective metal or plastic shaft. In use, the pocket thermometer can be hung by an eyehole on the shaft cap. It is a lightweight, compact instrument that provides a safe method for transporting a reasonably accurate thermometer. Although it can be carried in a pocket and removed for quick readings of air or water temperature, the best use is to hang it in a shaded location for periodic reference.

A simple minimum-maximum thermometer consists of a pair of liquid thermometers that are modified to mark the highest or lowest reading until they are reset. The marking mechanism can be a plug at the end of the liquid column or a constriction in the column, similar to an oral temperature thermometer. A minimum-maximum thermometer can provide the immediate temperature, and it can also track the range of temperatures during the measurement period. It is particularly useful in determining whether the air temperature drops below freezing overnight.

A ground or soil thermometer looks like a small, all-metal meat thermometer with a shaft that is pushed into the ground. The bimetal thermometer uses a dial display scaled to the appropriate range of soil temperatures. Often, bimetal expansion does not provide as accurate a measurement of temperature and, in some cases, the pointed metal shaft of a soil thermometer can present a hazard during transport.

A special set of thermometers is used to obtain the WBGT index. WBGT is the weighted sum of three temperatures: (1) a shaded air temperature, (2) a natural wet bulb temperature, and (3) a black globe temperature. T_a is conventional. The natural wet bulb is a thermometer with a wetted wick or cover exposed to the normal air movement (natural convection) described in the later section on Measurement of Humidity. The black globe thermometer is described in the following section on radiation measurements.

Radiation Measurement Instruments

Instruments for measuring radiation can be split into two categories: (1) thermometers and (2) direct radiation sensors. The simplest and most common instrument for measuring radiation is the Vernon black globe thermometer.[2] A black globe thermometer is part of the WBGT instrument set. The standard instrument is a 15-cm (or 6-inch) hollow copper sphere with a flat black outer surface and a thermometer inserted into the center. The flat black surface has high emissivity (ε) and absorptivity (α). The solar angle is unimportant, because a sphere always presents the same cross-section area perpendicular to solar beams. When air temperature and wind speed are known, the globe temperature, T_g, is used to compute the mean radiant temperature ($\overline{T}_r$), which represents the effect of radiation that would be emitted in a chamber with all walls heated to that temperature.[3] The theoretical basis for $\overline{T}_r$ is the Stefan-Boltzmann law that all bodies emit radiation in proportion to the fourth power of surface temperature in degrees Kelvin (°K). $\overline{T}_r$ goes in the reverse direction to determine the theoretical temperature of surrounding surfaces that would produce that level of isotropic radiation.

(A1) $\overline{T}_r = [T_g^{\,4} + 2.5 \bullet 10^8 \bullet V^{0.6} \bullet (T_g - T_a)]^{1/4}$.

One objection to the black globe thermometer as a radiation instrument is that it measures the combined effects of radiation, air temperature, and wind. Another problem is that many radiation sources are not isotropic. In particular, solar angle has a significant effect on the amount of direct solar radiation striking the body surface. Other objections include the globe color and the slow response time of the 15-cm globe thermometer. A variety of modified globe thermometers exist, including scaled-down spheres, flesh-colored surfaces that more closely simulate absorption by human skin,[3] an ellipsoid comfort meter,[4] and globes protected by transparent wind shields.[5] The modified globes are attempts to correct objections to the original globe while retaining the simplicity of operation and the concept of $\overline{T}_r$. Matthew and colleagues[6] have developed a method for approximating black globe temperature and $\overline{T}_r$ using a single radiation instrument as an alternative to the bulkier globe thermometer.

The alternative to $\overline{T}_r$ is to measure the separate incoming radiation components. This is the only way to obtain an accurate estimate of the amount of solar radiation, or solar load, reaching the body surface. Unfortunately, the investment in instruments and effort required to obtain separate values for the different radiation components is extensive.[7] With very few exceptions, weather stations make only one radiation measurement. Consequently, only a few investigators[8–11] have obtained enough of the data required to calculate accurately the actual solar load. Although a variety of different names are used to differentiate radiometers by function, most instruments follow the same basic design. A generic radiometer consists of a flat thermopile or photoelectric sensor disc covered

Fig. 8-A3. A pyranometer—a radiometer for measuring global solar radiation. On this instrument, the thermopile sensor is protected from convective heat loss by double-glass hemispheres. Hukseflux model LP02.
Photograph: Courtesy of US Army Research Institute of Environmental Medicine (Natick, Mass).

with a half dome of transparent material to protect the sensor surface from damage and convective heat loss (Attachment Figure 8-A3). Usually, the instrument mount incorporates levels so that the sensor can be mounted in a fixed position relative to the horizon. By using different orientations of the sensors, mounts that limit or block radiation from different sources and domes that filter out different segments of the electromagnetic spectrum, visible infrared, and sometimes ultraviolet, radiation can be separated into direct, diffuse, or sky, and reflected or ground components. To obtain continuous radiation data for the basic solar and infrared components requires a minimum of four or, preferably, five radiometers, plus at least one special instrument mount.[12] The majority of weather stations have limited or no radiation instrumentation.

Pyranometers, for example, are radiometers used to measure solar radiation. The sensor is covered by a glass dome that limits the spectral range to the near-ultraviolet, visible, and near-infrared spectra (300–3,000 nm). A level pyranometer exposed to the sky measures global radiation, which is a combination of direct and diffuse solar radiation. The previously noted relationship developed by Matthew and colleagues[6] to estimate $\overline{T}_r$ uses global radiation as the alternative to measuring black globe temperature. To separate direct and diffuse solar radiation, a separate value for diffuse or direct solar radiation must be obtained. A pyrheliometer is aimed directly at the sun to measure direct solar radiation. Diffuse radiation is measured with a pyranometer just like global radiation, except that a shadow-band mount or a disc is used to block direct radiation. A shadow band consists of a band of metal positioned at the correct (solar) angle to block the direct sun rays as the sun travels above the horizon from east to west. Lambert's cosine law and the solar angle are used to compute the intensity of the direct solar beam.[7,12,13] Reflected solar radiation is measured exactly like global radiation, except that the sensor is inverted so that only radiation from the ground reaches the thermopile. It is also possible to estimate reflected solar radiation by multiplying global radiation by the appropriate surface albedo.

Other radiometers use a polyethylene dome rather than glass to protect the sensor surface. The plastic is transparent to a broader spectrum (300–60,000 nm) of infrared radiation than glass; therefore, both short- and long-wave radiation are measured. By subtracting solar radiation from the total radiation, a value for infrared radiation can be obtained.

A combination of pyranometers and net radiometers can be used to determine the incoming radiation components. A net radiometer consists of two radiation sensors mounted back-to-back with plastic domes. When mounted horizontally, one of the sensors measures ground radiation, and the other sensor measures radiation from the sky. The signals from the two sensors are electronically subtracted to obtain a net value. A second net radiometer with one side covered with a metal cup[14] is used to determine the total sky radiation. From those four instruments, separate values for sky and ground infrared, plus direct, diffuse, and reflected solar radiation can be derived. Yet another radiometer with another filter is required to obtain a separate measurement for ultraviolet radiation.

The standard height for a black globe thermometer is 1.2 m (4 ft). For pyranometers that measure radiation from the sun and sky, the important factor is exposure rather than height. The sun is 150 • 106 km from the Earth—a meter closer or farther away will not make much difference. The sensor element should not be shaded by any surrounding vegetation or structure, nor should light be reflected off a wall or other surface.

Measurement of Wind Speeds

Outdoor wind speeds are often quite variable, and it is useful to record both the range and mean wind speeds. Another problem is the effect of objects and surface variations on wind speed. Wind speed varies with respect to height above ground, the texture or roughness of the ground surface, and any obstacles or surface variability that affect the flow of air. A variety of instruments are used to measure wind speed, including pressure, mechanical force, sonic, and convective or heated anemometers.[15] The two most common types are electrically heated anemometers that are used to measure convective cooling and mechanical instruments (eg, propeller and cup anemometer; see Attachment Figure 8-A4) that are used to measure wind force in one plane.

Hot-wire or heated-bead anemometers are often used indoors to measure lower air velocities, whereas the most common outdoor instruments are mechanical cup or propeller anemometers. Mechanical anemometers measure mechanical wind force in one plane, whereas heated anemometers measure convective heat loss to air. The inertia of mechanical anemometers generally limits their threshold sensitivity to low air velocities. From a physiological perspective, the heated anemometers measure the effects of turbulence and the more relevant factor of heat exchange. However, in an outdoor environment where air velocities are usually higher, the more rugged mechanical anemometers are the common choice.

Fig. 8-A4. Cup anemometer, which measures wind speed in a horizontal plane. MET ONE model 014.
Photograph: Courtesy of US Army Research Institute of Environmental Medicine (Natick, Mass).

Air movement close to the ground tends to be turbulent relative to air measured at standard weather station heights (1.2–10.0 m). The two basic wind parameters are (1) wind speed and (2) wind direction. Direction is clearly important if the military population varies in its exposure to the wind. A change in wind direction can change a relatively comfortable sheltered position into an exposed position or vice versa. Wind direction would, of course, also be critical in the event of a nuclear, biological, or chemical attack. Mechanical wind vanes or simple observations of wind direction with reference to a compass will usually suffice. The basis of a mechanical wind vane can be modified with a contact sensor to sense electronically the direction of the wind vane. Aside from the overall bulk, the only real objection to wind vanes is that the motion of the vane tends to draw attention.

Like wind direction, wind speed can be estimated by observation. The Beaufort wind scale (Attachment Table 8-A1) uses observations of the effect of wind on common objects (eg, flags and dry leaves) to estimate wind speed. Wind speed is measured with an anemometer. One type of anemometer operates on the basis of the Bernoulli principle. This simple anemometer or wind gauge is a plastic tube with a small, light bead inside that moves up and down as the wind blows across the open top of the tube. Wind speed is read from a scale on the side of the tube. A pitot tube can be used as a much more sophisticated version of the same sensor.[15,16] Other anemometers are based on the actual deflection of an arm against a known resistance. This type of simple gauge is often combined with a wind vane so that it is also orientated into the wind. The most familiar anemometers are cup or propeller anemometers that are rotated by the force of the wind. The number of rotations is counted electronically to calculate wind speed. Like wind vanes, these anemometers tend to draw attention.

Electronic Sensors

Cup anemometers (see Attachment Figure 8-A4) are relatively rugged, and some can actually generate an electronic signal. However, the stall speed, based on inertia of the cup assembly, limits the sensitivity of the instrument to a threshold value of $0.2\ m \bullet s^{-1}$ to $0.5\ m \bullet s^{-1}$. For greater sensitivity, an electronically heated anemometer can be used. These anemometers operate by measuring the power required to heat a small wire or bead to a constant temperature. The power demand is proportional to the convective heat loss from the heated element, and convection is directly related to air velocity. Convection, which includes the effect of turbulence in addition to the mechanical force of the wind, is measured. A cup anemometer is a direct measurement of wind speed in a single plane of rotation. A heated anemometer is based on the more physiologically relevant property of convection. Beaded sensors are usually more rugged than hot-wire anemometers and tend to be more omnidirectional in terms of exposure.

As noted previously, wind speed varies in relation to height above ground, the texture or roughness of the ground surface, and any obstacles or surface variability that influence the flow of air. Turbulence and variation in air velocity are caused by friction or drag between the surface and air. Consequently, the height at which wind speed is measured is important. The best solution is to measure wind speed at two heights, 0.5 to 2 m apart. In

TABLE 8-A1

BEAUFORT WIND SCALE

Beaufort No.	Wind Speed $m \cdot s^{-1}$	Wind Speed mph	Description	Specifications for Land Conditions
0	< 1	0.5	Calm	Calm; smoke rises vertically
1	1	2	Light air	Direction of wind shown by smoke drift
2	2	5	Light breeze	Wind felt on face; leaves rustle
3	4	9	Gentle breeze	Leaves and small twigs in motion; wind extends light flag
4	7	16	Moderate	Raises dust, loose paper; small branches moved
5	10	22	Fresh	Small trees in leaf begin to sway
6	12	27	Strong	Large branches in motion; whistling heard in overhead wires
7	15	34	Near gale	Whole trees in motion; some difficulty walking against wind
8	18	40	Gale	Breaks twigs off tree; impedes walking progress
9	20	45	Strong gale	Slight structural damage occurs
10	26	58	Storm	Trees uprooted; considerable damage occurs
11	30	67	Violent storm	Widespread damage
12	> 33	74+	Hurricane	Massive and widespread damage to structures

Adapted with permission from Lutgens FK, Tarbuck EJ. *The Atmosphere: An Introduction to Meteorology.* Englewood Cliffs, NJ: Prentice-Hall; 1979: 144.

addition, objects in the path of the wind (or fetch) have an effect. The general rule is that the fetch should be 10 times the height of an obstructing object.[17] It is often simply impractical and unrealistic to obtain an unobstructed fetch. Wind speed fluctuates rapidly and can vary considerably within a small distance. In areas with any significant topography or tall vegetation, wind parameters are very local. The degree of correlation between a remote weather station and local wind conditions can be tenuous.

Measurement of Humidity

Broadly defined, humidity is the moisture content of the air. Measurement problems arise in part because a number of variables can be used to describe humidity, including absolute humidity, dew-point temperature, relative humidity, psychrometric or aspirated wet bulb temperature, natural wet bulb temperature, and water vapor pressure. The situation is not helped when many of the variables can be expressed in multiple units. For example, water vapor pressure can be expressed in units of millimeters of mercury or torr (mm Hg) or kiloPascals (kPa). Psychrometric charts (Figure 8-3) illustrate the third complication, the nonlinear relationship between temperature and humidity. However, psychrometric charts also demonstrate that, given air temperature and one measure of humidity, virtually any other humidity variable can be derived.

Instruments for measuring humidity include natural wet bulb thermometers, sling psychrometers, dew-point thermometers, and various electronic capacitance devices. Each presents its own problems. Humidity sensors that use water are of limited utility when the temperature range falls below the freezing point of water, although some of the electronic sensors claim a lower limit of –40°C. In other cases, a modified dew-point thermometer is also used below freezing. To some extent, the question is irrelevant, because even at saturation, the vapor pressure of water at –40°C is only 0.01 kPa versus 2.34 kPa at 20°C. When saturated cold air is warmed, either by contact with the body surface or inside the lungs, the warmer air is no longer saturated and has a much greater capacity to absorb water. Hence, in an apparent paradox for humans, even saturated cold air is very dry. From a physiological perspective, the effect is primarily on the respiratory tract, because thermoregulatory sweating is often minimal in extreme cold.

Natural wet bulb thermometers, which are a standard component of WBGT instruments, are as reliable as any liquid thermometers, as long as the wick covering the ball is kept clean and wet. Unfortunately, the natural wet bulb (or naturally aspirated temperature) has little application except for WBGT. The measured temperature is a product of humidity, air temperature, and wind speed. Unlike the other measurements of humidity, water vapor pressure cannot be readily derived from the natural wet bulb. Gagge and Nishi[18] determined that, above

2.5 m • s^{-1}, natural wet bulb and aspirated wet bulb are essentially equivalent. Most people are familiar with the sling psychrometer, which has wet bulb and dry bulb thermometers on a mount that is rapidly rotated or whirled to obtain a relatively uniform velocity. The reason for using a sling psychrometer is to eliminate the effect of variation in wind speed on the wet bulb temperature reading. Objections to using the sling psychrometer include the following: (*a*) wick management, (*b*) errors in reading the two thermometers, (*c*) susceptibility to damage, (*d*) time required to obtain a reading, and (*e*) difficulty in replicating the measurement. Relative humidity is computed from the difference or wet bulb depression between dry bulb and wet bulb temperatures. A third type of mechanical humidity sensor is the hair hygrometer, which senses expansion and contraction of human hair under tension in relation to changes in humidity.

An aspirated psychrometer uses a small electric fan rather than the sling to maintain a constant air velocity over temperature sensors. Dew-point thermometers cool a small mirror until water condenses on the surface. Dew-point thermometers are accurate, but often complex instruments. The term "frost point" is used when temperatures are below the freezing point. Neither aspirated psychrometers nor dew-point sensors are particularly well suited to remote field use because of fragility, weight, or power requirements for the fan or cooling. Electronic humidity sensors measure electronic signals generated in response to the effect of humidity on a variety of sensor elements. Properties measured include the absorption or conductivity of salt solutions, thin film capacitance, and differential cooling surfaces. Calibration and stability are the primary concerns with many electronic sensors, but the wide variety of sensors available makes it difficult to generalize about this category. The best solution, when feasible, is to use a second humidity sensor. The two sensors can be mounted as a pair, or one can be mounted 0.5 m lower than the other. Electronic humidity sensor elements are often wafer thin, and power requirements for some sensors can be low. Consequently, electronic humidity sensors can be readily incorporated into the small environmental sensor suites described in the main text.

Other Meteorological Parameters

In addition to the four basic parameters that define the thermal environment—(1) temperature, (2) solar radiation, (3) wind speed, and (4) humidity—there are two other meteorological parameters that can significantly modify environmental effects on the soldier: (1) pressure, often an altitude effect; and (2) precipitation.

Pressure and Altitude

The original barometer used a column of mercury with one open and one closed end, with a vacuum above the mercury column. The open end is sensitive to pressure, which pushed the column of mercury up into the end with the vacuum.[19] Aneroid barometers use a metal diaphragm, which is usually a hollow disc of thin metal enclosing a cavity that is partially or completely evacuated with a spring inside. As pressure changes, the diaphragm expands or contracts. Changes in the diaphragm are electronically or mechanically translated into a pressure reading.

Altimeters are barometers that use changes in atmospheric pressure to determine altitude. Most altimeters are calibrated for changes in atmospheric pressure at a known elevation. Because altimeters usually include barometric pressure as an output, they can be used to calculate changes in barometric pressure from standard temperature and pressure. For greater precision, barometric measurements should be adjusted for temperature effects. Making adjustments for barometric pressure is important if a unit moves to a different elevation. Usually, over short periods of time, changes in pressure from elevation are greater than changes from variation in atmospheric pressure associated with movement of air masses. Altimeters also aid in the navigation of mountainous terrain.

Precipitation

Rain and snow have important effects on the overall operation of aid stations and medical evacuation operations. Simple rain gauges consist of a large collecting area, which funnels water into a smaller, scaled tube or gauge, so that even a small amount of rain can be read off the gauge. More elaborate instruments, including weighed or tipping rain buckets and raindrop detectors, are also available. Stream depth gauges are used to predict flooding and depth of immersion to monitor hazards for stream fording by both individuals and vehicles. Snow depth is sometimes read in a bucket or larger diameter gauge, but it is common to simply insert a scale or gauge into the snow. Snow depth can be read easily by allowing it to accumulate on a flat bench, using a ruler to measure the depth, and then sweeping the bench clear for the next accumulation of snow. A more precise measurement of the weight of precipitation is to collect the snowfall, then melt it down to the liquid water equivalent. This can be more important in determining snow loading on tents, but snow removal is a function of both weight and volume.

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